AFIT/GEE/ENV/95D-03

IN SITU SOIL WARMING AND SOIL VENTING TO
ENHANCE THE BIODEGRADATION OF JP-4 IN COLD
CLIMATES: A CRITICAL STUDY AND ANALYSIS

THESIS
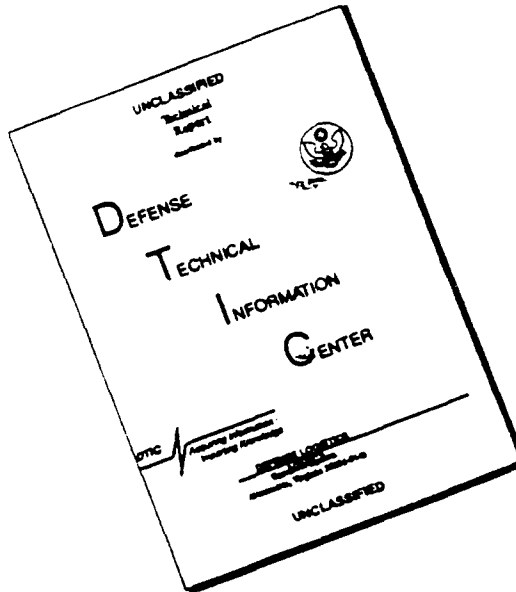
Ricky D. Cox, Captain, USAF

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Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Engineering and Environmental Management

Ricky D. Cox, B.S.

Captain, USAF

December 1995

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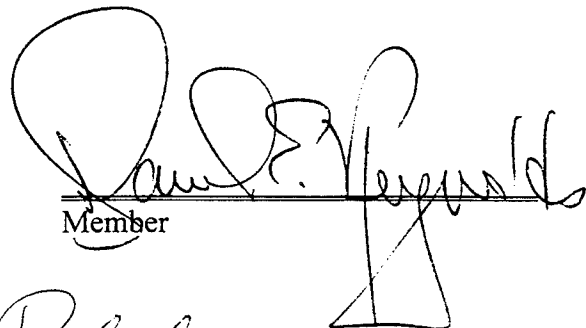
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Member   Member

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Chairman

Acknowledgments

<div align="right">Rick Cox</div>

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Abstract

Numerous bioremediation projects have proven effective in accelerating

contaminant biodegradation by injecting oxygen into the soil with a technique called

bioventing. In cold climates, in situ bioremediation is limited to the summer when soil

temperatures are sufficient to support microbial growth. Laboratory studies directly

correlate increased biodegradation rates with temperature. Raising soil temperatures can

accelerate jet fuel remediation which was shown by a bioventing project conducted in

1991 at Eielson AFB, Alaska, where three soil warming techniques were used. Two

methods actively warmed the soil -- warm water circulation and heat tape; the other

passively warmed the plot with insulatory covers. Microbial respiration (O_2

consumption) at the test plots was compared to an uncontaminated area and an unheated,

contaminated, control plot. This study critically analyzed the project data to determine

the effectiveness of enhancing biodegradation. This study also modeled the temperature-

biodegradation relationship at the test plots using the van't Hoff-Arrhenius equation.

Using paired oxygen consumption rates and temperatures, the equation was valid only for

the warm water and passive warming plots. This study demonstrated that, in cold

climates, bioremediation is feasible and can be enhanced by soil warming. Soil warming

can decrease remediation time with acceptable cost increases.

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I. Introduction

1.1 General Issue

A major problem facing the world today is the extent of soil and ground water contamination from hazardous and toxic chemical spills. The National Priority Listing contains more than 1200 contaminated sites, and potentially more than 32,000 sites could be listed. A significant number of the nation's 7 million underground storage tanks may also be leaking (Baker, 1). The handling and transport of huge volumes of petroleum products, approximately 800 billion gallons per year, is a frequent source of contamination of groundwater systems (Chapelle, 322). The costs for contamination cleanup are taking an increasing portion of the government's budget. In fiscal year 1993, the Department of Defense set aside $1.2 billion for cleanup projects with another $444 million designated for military bases scheduled for closure. The DoD's restoration priority list contains about 12,000 sites at active military installations worldwide (Kim et al., 31). The importance of finding low cost solutions to historically expensive cleanup efforts cannot be overstated. Recently, bioremediation has emerged as an acceptable low cost, low intensity technique in remediating biodegradable contamination present in groundwater and soil.

1.2 Specific Problem

Many bioremediation projects have limited success due to restricted levels of oxygen and conditions for microbial growth. Since 1990, numerous projects and laboratory studies have focused on providing oxygen to facilitate microbial activity. As a result, a technique called bioventing has been discovered and found effective in delivering oxygen into the soil. However, providing sufficient oxygen does not guarantee success for every bioremediation project, especially in colder climates. At the northern latitudes, bioremediation is restricted to the summer months when soil temperatures reach a level conducive for microbial activity. With many oil spills from defense and oil exploration activities, biodegradation of petroleum contamination in arctic environments may be enhanced by increasing and maintaining higher soil temperatures. Before 1991, no bioremediation project had been attempted that maintain conditions sufficient for microbial activity in the winter months. Although the technical protocol for bioventing had not yet been developed in 1991, project managers for a JP-4 jet fuel contamination site at Eielson AFB took a bold step when they began their bioremediation efforts in a year-round cold climate application.

Temperature is an important variable in the sub-surface environment. Given sufficient oxygen, increasing soil temperature to an optimal level will enhance biodegradation. This was a central focus of the Eielson AFB project. There, project managers employed three different heating methods to warm the soil with all

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contaminated plots being biovented. These methods -- warm water, passive warming, and heat tape -- were compared to a contaminated control plot and an uncontaminated background area. Nearly all plots were installed in July 1991 with the initial goal of comparing the effectiveness of active versus passive warming methodologies. In summer 1992, the U.S. Environmental Protection Agency became more involved with the project by funding the surface warming technique.

This thesis examines the effectiveness of the soil warming techniques on raising soil temperatures and enhancing biodegradation. Additionally, other passive and active soil warming techniques will be reviewed. Soil warming techniques involve heating soils to temperatures lower than 40 °C. This should not be confused with soil heating or other thermal technologies, in situ and ex situ, which heat soils to temperatures much greater than 50 °C.

The principle objective of the Air Force study at Eielson AFB was to operate an in situ bioremediation project in a subarctic environment while examining the feasibility of using bioventing technology to remediate JP-4 jet fuel contamination. EPA objectives were to actively increase soil temperature and determine to what extent higher temperatures improve biodegradation rates. Together, the Air Force and EPA sought to maximize the biodegradation of JP-4 while minimizing its volatilization and subsequent air emissions (Battelle, 2). Using data from the Eielson AFB project, the biodegradation rate and temperature relationship will be explored. Additionally, several bioremediation

case studies in the arctic and other relevant research will be discussed that are related to soil temperature and biodegradation in cold climates.

1.3 Research Objectives

The objectives of this research are as follows:

(1) Investigate the relationship between soil temperature and the hydrocarbon biodegradation rate using data from a project completed at Eielson AFB, Alaska where bioventing was coupled with soil warming.

(2) Investigate the efficacy of different warming techniques to increase soil temperature and remediate JP-4 contamination.

(3) Review in-situ active and passive heating techniques to increase hydrocarbon biodegradation rate. Active techniques include heated air injection, heated water injection, and electric tape. Passive methods include soil covers, irrigation, tilling, vegetation, composting, and solar energy.

(4) Examine effectiveness of bioremediation efforts in cold climates.

(5) Examine the cost and remediation effectiveness of techniques utilized at Eielson AFB, Alaska.

1.4 Abbreviations Used in this Study

°C	degrees Celsius
°F	degrees Fahrenheit
AFB	Air Force Base
BTEX	Benzene, Toluene, Ethylbenzene, and Xylene compounds
cm	centimeter
CRREL	Cold Regions Research and Engineering Laboratory (U.S. Army Corps of Engineers)
DDT	Dichlorodiphenyl trichloroethane
DoD	Department of Defense
DOE	Department of Environment (State of Alaska)
ft	feet

Hz	Hertz
GHz	Gigahertz
ISRT	In Situ Respiration Test
kcal	kilocalorie
km	kilometer
l	liter
m	meter
min	minute
PCB	Polychlorinated Biphenyl
PCE	Perchloroethylene
RF	Radio Frequency
SVE	Soil Vapor Extraction
TCE	Trichloroethylene
TPH	Total Petroleum Hydrocarbons
TVH	Total Volatile Hydrocarbons
Vadose Zone	The unsaturated soil between the surface and the saturated zone
VOC	Volatile Organic Compounds
W	Watt

II. Literature Review

2.1 Bioremediation

A principal advantage of bioremediation is that wastes are treated permanently thus eliminating long-term liability. The fundamental principle of bioremediation is the conversion of organic wastes into CO_2, CH_4, and inorganic salts. In order to successfully bioremediate a site, sufficient oxygen, nutrients, and moisture must be present in the sub-surface (Charbeneau, 117). Bioremediation is a biochemical reaction mediated by microorganisms naturally occurring in the sub-surface. These microorganisms are predominantly bacteria that degrade contaminants by gaining energy in the process allowing them to grow and reproduce. In an oxidation-reduction reaction, the microorganisms gain energy by breaking chemical bonds and transferring electrons from the source contaminant to an electron acceptor, preferably oxygen (National Research Council, 18). Although, reactions may occur anaerobically, the level of oxygen present in the aquifer has been identified as a rate-limiting variable. Otherwise, an anoxic dependency on alternate electron acceptors such as nitrate, sulfate, or carbon dioxide will exist (Charbeneau, 117). Furthermore, the anaerobic degradation of petroleum hydrocarbons occurs at much lower rates (Leahy and Colwell, 307).

Aerobic degradation is preferred since more energy is available for utilization by microorganisms. The chemical equation for the aerobic mineralization of hexane (C_6H_{14}) follows:

$$C_6H_{14} + 9.5O_2 \rightarrow 6CO_2 + 7H_2O \qquad (1)$$
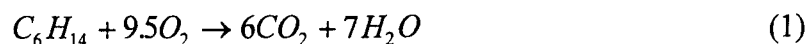
Equation (1) indicates that bioremediation is shown by an increased concentration of

inorganic carbon present as CO_2 and decreased levels of oxygen and hexane (National

Research Council, 23). By converting the reactants from moles to grams, 3.54 grams of

oxygen is required to mineralize each gram of hexane present.

Bioremediation is only viable for those contaminants that are biodegradable. The

following table shows the biodegradability of several organic hazardous wastes (Leahy

and Brown, 109):

Table 1: Biodegradability of Organic Hazardous Wastes

Readily Degradable	Moderately Degradable	Hard To Degrade
Gasoline	#6 Oil	TCE
Jet Fuel	Crude Oils	PCE
Diesel Fuel	Lubricating Oils	Vinyl Chloride
Toluene	Coal Tars	PCBs
Benzene	Creosotes	DDT
Isopropyl Alcohol	Pentachlorophenol	Chlordane
Methanol	Nitrobenzene	Heptachlor
Acetone	Aniline	
Ketones	Long-chain aliphatics	
Phenols	Phthalates	
Acrylonitrile		

As indicated above, medium fuel petroleum distillates, such as jet fuel and diesel fuel, are

biodegradable if natural microorganisms are not limited by oxygen or nutrients (Atlas,

429). Bioremediation of a site is often an impossible task and there are many limiting

factors. Given sufficient oxygen, temperature and moisture content seem to be the

principal constraints for success. There have been numerous success stories of

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contaminant clean-up by using bioremediation techniques and several will be discussed here.

2.2 Bioventing

Bioventing has emerged as a technique to provide oxygen to the sub-surface. Bioventing applications deliver oxygen to unsaturated soils by injecting air, thus enhancing the biodegradation of organic contaminants (Fredrickson, 1714). Because oxygen is typically a limiting factor in soil, bioventing has been proven to be an efficient and cost-effective means of delivering sufficient oxygen. In fact, the limiting factor for the microorganisms may eventually become the contamination due to its unavailability or low concentration (Reisinger et al., 46). Although bioventing can enhance groundwater remediation by increasing dissolved oxygen levels, it is primarily an in-situ soil remediation technique (Miller (1993), 1). Bioventing is similar to other soil venting processes such as soil vacuum extraction, soil gas extraction, or in situ soil stripping. Soil venting maximizes volatilization of low weight compounds whereas "bioventing is designed to maximize biodegradation of any aerobically biodegradable compound, regardless of molecular weight, while minimizing volatilization" (Leeson et al., 284). Using lower flow rates, bioventing combines the advective soil venting processes with biodegradation. With bioventing, biodegradation is the primary remediation mode with advective venting a minor component (Reisinger et al., 45,47).

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Bioventing has been proven to be a successful method to clean-up numerous sites in the temperate and subtropical regions of the United States (Ong et al., 444). Its objective is to engineer an oxygen flow rate that maximizes biodegradation and meets the microbial oxygen demand while minimizing VOC emissions. An air flow rate too high may volatilize the contaminant and produce unwanted aboveground emissions. For shallow contamination, uncontrolled migration of VOCs may result from even low levels of air injection. If emissions are too high, project managers may be forced to capture and treat the off-gases before their release into the environment. The efficiency of bioventing is improved by a long air flow path, large volume of soil contact, and a high vapor retention time in the soil. By increasing vapor retention time, aboveground treatment of the off-gas becomes unnecessary (Newman and Martinson, 280).

Bioventing is not only a less expensive clean-up technique, it decreases the remediation time by reaching contamination deep in the ground. This has been demonstrated by a project at Hill AFB, Utah. There, bioventing was conducted at depths of 35 to 95 feet with average biodegradation rates of 36 to 360 mg/kg soil/year (Fredrickson, 1715). Bioventing is most effective in remediating medium weight fuels with a low to medium volatility, such as jet fuel. A site contaminated with jet fuel will require less bioventing time than one with a fuel such as diesel (Brar, 127).

Bioventing is a preferred cost-effective alternative to deliver oxygen since ambient air is 20.9% oxygen and available at virtually no cost. The level of oxygen demand for biodegradation of a hydrocarbon contaminant varies by the degree of fuel

saturation in the soil and the amount of carbon fixed as biomass, as well as the amount of carbon completely oxidized to carbon dioxide. Conservative estimates for oxygen demand assume that all carbon is oxidized to carbon dioxide (Newman and Martinson, 284). Complete degradation of a pound of hydrocarbons requires 3 to 3.5 pounds of oxygen. To deliver one pound of oxygen, 60 ft^3 of air is required (Leahy and Brown, 108). Furthermore, delivering oxygen to the soil matrix by air injection distributes oxygen more efficiently than relying on water as an oxygen source due to the higher diffusivity and lower coefficient of friction of air (Reisinger et al., 47). Having limited solubility in water, O_2 rapidly becomes limiting in the presence of excess biodegradable organic carbon (Fredrickson, 1712).

Another method to deliver oxygen is the injection of water. However, it is extremely difficult to deliver sufficient oxygen to a contaminated site by using water. An enormous volume of water, approximately 80,000 kg, would be required to degrade 1 kg of hydrocarbon given a concentration of 40 mg/l of dissolved oxygen in water (Reisinger et al., 46). Compared to a stoichiometric ratio of water to hydrocarbon of over 10,000:1, only 5.9 kg of air is required to provide minimum oxygen (Leeson et al., 285). Furthermore, low permeability soils inhibit the flow of water through a site thereby, preventing oxygen from reaching much of the microbial population. In a typical 1 m^3 of dry sand having a porosity of 0.4 and contaminated with 10,000 mg/kg of hexane, 6056 m^3 or 15,500 pore volumes of water is required to aerate each m^3 of contaminated soil with oxygen saturated water (Miller (1990), 26). In the past, other means such as

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hydrogen peroxide have been used to deliver oxygen to the soil. In a hydrogen peroxide solution of 500 mg/l, the volume of water required is reduced to approximately 13,000 kg per 1 kg of hydrocarbon (Reisinger et al., 46). Numerous studies have concluded that the rapid decomposition of hydrogen peroxide makes it a poor source of oxygen.

Bioventing is the most effective technique to provide oxygen to the sub-surface for an in situ bioremediation project. It is calculated that given 21 % oxygen in air and 9 mg/L in water, air "has a twenty-fold greater oxygen content on a mass per unit volume basis" and is much less viscous than water (Miller (1990), 33). Miller was involved in developing the Air Force test plan and technical protocol used in a field treatability test for bioventing. He asserts that bioventing has shown great effectiveness for BTEX compounds but mixed results for TPH. He states that bioventing is feasible in most soils; however, temperature may be the greatest stimulant to biodegradation (Miller (1995)). As a result of his efforts, the Air Force launched a bioventing initiative in April 1992 to test its effectiveness at 55 contaminated sites. This effort was endorsed by the senior leadership of Air Force Civil Engineering and the U.S. EPA.

As stated before, bioventing has been shown to be a low-cost remediation technique. Soil vapor extraction costs at a test site at Patrick AFB, Florida, were $345 per day with cost per kilogram of TVH destroyed ranging from $0.88 to $16.32. After the site was converted to a bioventing application, costs decreased to $33 per day. Project managers point out that despite the additional time required for remediation, 10 months of bioventing can be completed for the same cost as one month of SVE (Downey

et al., 256). Based on numerous Air Force projects, bioventing costs are within $10-$50

per cubic yard. For sites with over 10,000 cubic yards of contaminated soil, costs less

than $10 can be achieved. Similarly for very small sites, higher costs may result (Miller

(1993), 12).

2.3 Temperature and Biodegradation Rate Relationship

The presence of bacteria is limited by numerous factors in the abiotic

environment: water content, soil temperature, pH, electron acceptors, and other nutrients.

Soil temperature is a key element for the success of a bioremediation project. Microbial

life is supported by a series of enzymatically catalyzed chemical reactions. As

temperature increases, the rates of these chemical reactions tend to increase. The

enzymes and nucleic acids that catalyze these reactions are both heat-sensitive.

Furthermore, excessive heat will alter the structure of nucleic acids distorting stored

information in the microorganism. A microorganism's suitable temperature range is

defined by the curve shown in Figure 1 below which contains three values called cardinal

temperatures and describes the organism's growth rate versus temperature (Chapelle, 52-

53).

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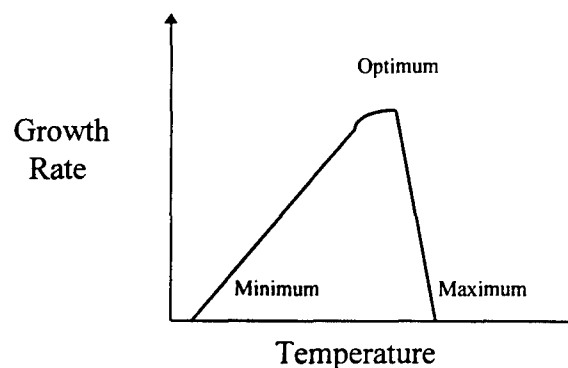
Figure 1: Growth Rate versus Temperature

1. *Temperature minimum* is the lowest temperature that the organism can survive and grow. Above this point, growth rate will increase.
2. *Temperature optimum* is the temperature at which the organism's maximum growth rate occurs. At higher temperatures the growth rate decreases.
3. *Temperature maximum* is the highest temperature at which the organism can grow (Chapelle, 52-53).

Microorganisms are classified by the range of their cardinal temperatures. Those with a low cardinal temperature, 0 - 20 °C, are called psychrophiles and are typically found in cold environments and ocean floors. At temperatures below freezing, microbial cells become inactive and ice crystals may form. Cellular structures and membranes may be disrupted by freezing which could kill the organism. In laboratory analysis, rapid freezing techniques, which prevent ice crystal formation, are utilized to preserve organisms. The most common type of organisms, mesophiles, have a temperature range of 20 to 40 °C. With a body temperature of 37 °C, this is also the preferable range for humans. At environmental temperatures above 45 °C, thermophiles exist with an optimum range of 55 to 60 °C (Chapelle, 52-53).

Extremely hot or cold temperatures will prevent bacteria from surviving. Most soil bacteria are adapted to temperatures ranging from 10 to 15 °C. Above 30 °C, they become inactive although some thermophilic bacteria have been found effective at temperatures above 70 °C (Leahy and Brown, 112). Numerous laboratory studies have shown that biodegradation rates are inhibited at temperatures as low as 5 °C (Baker, 217).

However, it is reported that a bacteria isolated from a petroleum-contaminated soil in Antarctica was capable of actively degrading hydrocarbons at 1 °C (Baker, 13). At the project conducted at Eielson AFB soil temperatures were increased from 4 to 35 °C. This temperature increase did not detrimentally affect the microbial population. This is an interesting observation. One would think that the psychrophilic microorganisms indigenous to the cold Alaskan sub-surface could not cope with a soil temperature increase of this magnitude. Instead, as illustrated later, the project showed that increased soil temperatures resulted in higher microbial respiration rates. It is not surprising that the microorganisms cope with this temperature change. By developing a different set of enzymes, the microbes become able to survive with the change when they are not prone to function metabolically. Enzyme changes may be induced by the availability of food or changes in the environment, which must occur in order for the organism to survive. This project is one of many ongoing in Alaska but the others only occur in the summer months when ambient conditions are suitable for microbial activity to degrade petroleum contaminant products.

For oil spills, oil viscosity increases at lower temperatures, "volatilization of toxic short-chain alkanes is reduced, and their water solubility is increased, delaying the onset of biodegradation" (Leahy and Colwell, 307). It is widely accepted that for every 10 °C increase "within the tolerance range of the enzyme results in a doubling of activity" for the microorganism (Atlas, 219). This doubling of activity is predicted by the van't Hoff-Arrhenius equation which will be discussed in greater detail later. Early results of the

Eielson project demonstrated that a plot undergoing continual warming had a biodegradation rate of 6 mg/kg/day, approximately 3 to 4 times greater than those plots under ambient conditions (Battelle, 97). These results are consistent with other studies which show as much as a quadrupling of microbial activity for a 10 °C temperature increase (Baker, 215). Conversely, biodegradation also influences the soil temperature by producing heat. Complete oxidation of hexane produces 11,500 cal/g. In a study by Miller and Hinchee, biodegradation generated heat at approximately 12 cal/g soil. Heat loss to hydrocarbon evaporation was about 0.07 cal/g of soil which could partially explain the elevated soil temperatures noted by project managers during the study (Smith and Hinchee, 7-8). To put this in perspective, the latent heat of fusion of water, the amount of heat liberated from water freezing, at atmospheric pressure and 0 °C equals 80 cal/g. Conversely, in order to melt ice under those same conditions would require 80 cal/g of ice with no change in temperature (Jumikis, 76). While heat generated by biodegradation may not significantly alter the soil temperature, evaporation or condensation may. For example, the heat of vaporization of water at 20 °C is 590 cal/g and 85 cal/g for hexane (Smith and Hinchee, 7).

2.4 *Monitoring and Measuring Biodegradation Activity*

In developing a system to measure bioremediation performance, special consideration should be given to its design and placement. Monitoring wells should be positioned within the plume and at a depth such that relevant parameters are measured.

These parameters include: (1) individual hydrocarbon components; (2) dissolved oxygen; (3) nitrate; (4) dissolved iron; (5) redox potential; (6) carbon dioxide; (7) pH; and (8) total organic carbon. Carbon dioxide and pH are monitored "to evaluate the extent of bacterial respiration and determine if conditions are suitable for biodegradation." If the pH falls outside of the range 5 to 9, biodegradation can be inhibited (Borden, 9-13). Placement of monitoring wells depends on a site's spatial variation which is complicated by soil heterogeneity, contaminant distribution, and microbial distribution. To overcome these complications, extensive site characterization is required which is performed by drilling numerous wells and boreholes. It is estimated that a site with 4 borings per acre and each boring 8 inches in diameter will allow characterization of only 0.008% of the subsurface volume (Fredrickson, 1711-1712).

As stated earlier, biodegradation of hydrocarbons is a biochemical reaction which converts organic wastes into CO_2, CH_4, and inorganic salts. Microorganisms use the energy gained for cell maintenance and growth; however, measurement of microbial growth is impossible in field conditions. Microbial oxygen consumption and carbon dioxide production can be estimated by subsurface monitors. Field researchers have relied on measuring carbon dioxide levels in soil as an indication of microbial activity. If increasing levels of CO_2 correspond with decreasing levels of O_2 this indicates that contaminant degradation is occurring, i.e., the microbes are consuming O_2 while producing CO_2. But, measurement of CO_2 may overestimate respiration rates since production of this gas may be due to other factors (Chapelle, 184-185).

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Alternate measures of microbial activity and biomass such as heat output and hydrolysis measurement require more extensive monitoring and are of dubious accuracy (Chapelle, 185-186). Another monitoring approach is the measurement of the stable carbon isotope ratio in the soil gas carbon dioxide. This inexpensive test can distinguish CO_2 produced by degradation from that produced by other biotic activities. Aggarwal and Hinchee state that "during the growing season, CO_2 in soil gases at uncontaminated locations is derived dominantly from plant root respiration and from decaying organic matter; in other seasons the isotopic composition of soil gas carbon dioxide is influenced by atmospheric carbon dioxide" (1178-1179). Their study showed that higher CO_2 concentrations were found at remediation sites where soil venting had ceased.

At bioventing sites, the principal measure used to biodegradation rates is by conducting an in situ respiration test where oxygen depletion is monitored. This test is a rapid method which involves turning off the air injection and monitoring changing levels of O_2 in the soil. Numerous monitoring points are installed at varying depths and locations within the unsaturated zone of the contaminated soil. Monitoring points are located 15 to 20 feet apart. After shutting down the air injection, an initial reading is taken with subsequent readings every 4 to 8 hours. The test is terminated when oxygen concentrations are about 5 % of the soil gas or after 5 to 7 days of sampling (Hinchee and Ong, 1306). The O_2 readings are compared to uncontaminated background monitoring points (Hinchee et al., 19). It is assumed that microbial respiration is responsible for the consumption and decreasing levels of oxygen.

The data measured during the in situ respiration tests are used to compute O_2 consumption rates (%O_2/hr). Oxygen consumption rates are determined for each soil gas probe during each test. At a location near the Alaskan coast, researchers computed the O_2 consumption rate using the first few data points since those formed the linear portion of the curve. Based on the initial linear portion of the decay curve, oxygen consumption rates were calculated as zero order (Battelle, 51). This zero order kinetic relationship was validated by a project conducted at Tyndall AFB, FL (Miller (1990), 155). As the concentration of O_2 lowers, diffusion plays a larger role. In other words, as time increases the migration of oxygen gas through the sub-surface may prevent researchers from determining the true consumption occurring at a specific point. In some cases, oxygen levels may increase. Additionally, researchers have found that most vented sites have oxygen levels maintained at 10 % (Hinchee and Ong, 1309).

To ensure that the monitoring points are measuring the air injected, a helium tracer study is performed where 1 to 2 % helium is mixed with air. If helium is measured at a distant point, it is evidence that the soil gas being measured is that injected. Researchers validated this testing methodology at eight contamination sites located in different geologic and climatic conditions (Hinchee and Ong, 1306). Corresponding to decreasing concentrations of O_2 is an increase of CO_2 production. Dependence on CO_2 levels as an indication of microbial activity is unreliable. This is especially true in alkaline soils such as Eielson AFB. As soil pH increases, CO_2 produced during microbial respiration is more likely converted to carbonates as discussed earlier. Numerous

projects have demonstrated this, i.e., biodegradation rates based on CO_2 measurements decrease with increasing pH. When the oxygen and carbon dioxide levels were plotted over time, the CO_2 plots showed more scatter. This is due to the conversion of carbonates in alkaline soils and described by equation (2) below.

$$CaCO_3 + H_2O + CO_2 \rightarrow 7HCO_3^- + Ca^{2+} \qquad (2)$$
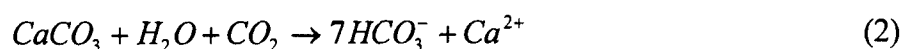
Therefore, CO_2 production may not be an accurate and dependable measure of biodegradation (Hinchee and Ong, 1309-1310). In addition to pH and moisture content, carbon dioxide production may be underestimated due to adsorption onto soil particles (Newman and Martinson, 284).

In calculating biodegradation rates, several assumptions about the site and underlying soil characteristics must be made.

(1) Effective air porosity of the soil = 0.30.

(2) Bulk density of the soil = 1,440 kg/m^3.

(3) The stoichiometric equation for the mineralization of hexane to CO_2 and water applies (see Eq (1)).

Previous studies have discovered biodegradation rates ranging from 0.4 to 13.0 mg-hexane/kg-soil/day for jet fuel (Hinchee and Ong, 1310). A bioventing study conducted by Miller found an average rate of 8 mg/kg/day at Tyndall AFB, Florida (1990).

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2.4.1 Biodegradation Rate Predicted by van't Hoff-Arrhenius Relationship

The van't Hoff-Arrhenius equation estimates the effect of temperature on biodegradation. Developed for aqueous systems, the equation is an excellent model for predicting temperature effects on contaminant biodegradation (Miller (1993), 3). Although it is preferable that the relationship be applied over a wide temperature range, it was validated by a bioventing project at Tyndall AFB, FL and the focus of a Ph.D. dissertation by Miller.

$$K_T \cong K_0 e^{-\frac{E_a}{RT}} \qquad (3)$$

where K_T = *temperature corrected biodegradation rate* (% O_2/day)

K_0 = *frequency factor* (% O_2/day)

E_a = *activation energy* (cal/mol)

R = *gas constant* (1.987 cal/°K.mol)

T = *absolute temperature* (°K) (Battelle, 109).

At sites in Alaska, Nevada, and Florida, the van't Hoff-Arrhenius relationship accurately predicted biodegradation rates within the 17 to 27 °C range (Smith and Hinchee, 10). In the project at Tyndall AFB, FL, the equation proved an excellent model accounting for temperature. Although soil temperature varied by only 7 °C, biodegradation rates were almost twice as high at 25 °C than at 18 °C (Miller (1990), 144). The study also confirmed the dependency of biodegradation on temperature finding it responsible for most variation observed at the in situ bioventing site (Hinchee and Ong, 1311).

Given a baseline biodegradation rate, this relationship is the most accurate

predictor of biodegradation as a function of temperature. By plotting the natural logarithm against the temperature inverse, called an Arrhenius plot, one can determine the frequency factor and the activation energy as indicated below.

$$\ln K_T = \ln K_0 - [(\frac{E_a}{R}) \times (\frac{1}{T})] \qquad (4)$$

The intercept of the plot is given as $\ln K_0$ and the slope is $-E_a/R$ with $1/T$ as the independent variable.

A key factor in the Arrhenius equation is the activation energy, E_a, which can be described as the amount of energy required to initiate the chemical reaction. Miller discovered that the activation energy for the in situ biodegradation of jet fuel at Tyndall AFB varied between 7.9 and 12.9 kcal/mol for two different treatment plots ((1990), 142). Another important factor in the equation is K_0, commonly called the frequency or pre-exponential or factor. In this context, K_0 can be imagined as the biodegradation rate at infinite temperature or when activation energy approaches zero (Bunce, 171). Determining the frequency factor has a strong dependence on temperatures observed at a site. This frequency factor is based on biodegradation and its rate of kinetics with changing temperature.

Use of the van't Hoff-Arrhenius relationship is based on two principal assumptions when examining the change in temperature and biodegradation over time. First, the contaminant concentration is constant over time. For example, this assumption ignores the decreased availability of petroleum with remediation over time which would result in reduced microbial respiration rates. Second, the amount of active biomass

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remains constant over time. Measuring the active microbial biomass accurately at a field

site is extremely difficult and expensive. In the initial growth phase, such as following

the first injection of oxygen at a site, microbial growth will increase significantly for a

short period of time. Given sufficient nutrients, a preferable temperature, and the

availability of contamination, microbial growth will stabilize until it is affected by one of

these factors. This second assumption ignores the effect of freezing temperatures and

reduced contamination concentration on the active biomass. Both factors, contaminant

concentration and amount of active biomass, are accounted for in the K_0 term of the van't

Hoff-Arrhenius equation (Sayles, Personal Communication).

Bunce states "the basis of the Arrhenius equation is that E_a is independent of

temperature" (171). Over a large temperature interval, curved plots may be obtained

instead of straight lines implying another exponential term is involved (Bunce, 171-172).

A non-linear Arrhenius kinetic relationship was examined in numerous experiments with

carbonaceous solids. The study suggested that despite a high linear correlation, data may

be better modeled by a curve fit (Cuesta et al., 1141-1145).

2.4.2 Biodegradation Rate Based on Universal Gas Law - Hinchee & Ong

Hinchee and Ong developed the methodology below for calculating

biodegradation rates by converting O_2 consumption rates, K_{O2} [% O_2/hr], to K [mg-

hexane/kg of soil/day] (1311-1312).

Using the partial pressure law with P = pressure of air in soil.

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$$k'[atmosphere/day] = 24 \times (^{K_{o2}}\!/\!_{100}) \times P \tag{5}$$

Applying the Universal gas law ($PV = nRT$) and converting k' to moles/m³ of soil gas/day with

R = universal gas constant [(atm m³) /(g mole °K)]

T = temperature (°K)

$$k''[gas\ moles/m^3\ (soil\ gas/day)] = 24 \times (^{K_{o2}}\!/\!_{100}) \times P \tag{6}$$

Multiply k'' by the effective gas porosity and dividing by the soil bulk density, the rate is converted to

$$k'''[oxygen\ moles/kg\ (soil/day)] = 24 \times (^{K_{o2}}\!/\!_{100}) \times {}^{P}\!/\!_{(R \times T)} \times (^{\Theta}\!/\!_{\rho_b}) \tag{7}$$

where Θ = effective air porosity

P = volume of air (m³) / volume of soil (m³)

ρ_b = bulk density of the soil (kg/m³)

Hexane is the assumed representative compound in the soil and the mineralization of such was given by equation (1). For each mole of hexane , 9.5 moles of oxygen are required and the rate equation now becomes:

$$K[mg\ hexane\ /\ kg\ soil/day] = 24 \times (\frac{K_{O2}}{100}) \times \frac{P}{R \times T} \times (\frac{\Theta}{\rho_b}) \times (M.W.\ of\ hexane \times \frac{1000}{9.5}) \tag{8}$$

Assuming: Θ = 0.30

P = 1 atmosphere

ρ_b = 1,440 kg/m³

R = 82.05 x 10⁻⁶ (atm m³) /(g mole K)

M.W. (molecular weight) of hexane = 86

The biodegradation rate based on oxygen consumption becomes:

$$K\ [mg\ hexane/kg\ soil\ /\ day] = 5516 \times K_{O2}\ {}^{[\%O_2/hr]}\!/\!_{T\ [°K]} \tag{9}$$

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For computation of biodegradation based on carbon dioxide production, a 25 % conversion efficiency is assumed and also found in Hinchee and Ong (1311-1312). Based on the mineralization of hexane as shown above, the rate equation now becomes:

$$K = 11,646 \times \frac{K_{CO2} \ [\%CO_2/hr]}{T \ [^\circ K]} \tag{10}$$

2.4.3 Biodegradation Rate From Bioventing Test Plan and Technical Protocol

Project managers for the Eielson AFB bioventing study calculated the biodegradation rates by using a relationship simplified from that developed by Hinchee and Ong. The biodegradation rate equation used was the result of a joint effort between Battelle Columbus Operations, U.S. Air Force, and the U.S. EPA. Together they published a test plan and technical protocol for bioventing projects which included the methodology to determine biodegradation based on oxygen consumption. Since respiration rates at numerous projects were observed to be zero-order, oxygen consumption rates can be obtained from the initial linear portion of the respiration curve. Based on the mineralization of hexane, the relationship is explained as follows (Hinchee et al. (1992), 50-54):

$$K_B[mg \ hexane \ / \ kg \ soil/day] = \frac{-K_{O2} \times A \times D_O \times C}{100\%} \tag{11}$$

where K_B = biodegradation rate

K_{O2} = oxygen consumption rate (%/day)

A = volume of air/kg of soil (l/kg)

D_O = density of oxygen (mg/l)

C = mass ratio of hydrocarbon to oxygen required for mineralization

with the following assumptions:

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Porosity = 0.30

Soil bulk density = 1,440 kg/m^3

D_O = oxygen density of 1,330 mg/l

C = 1:3.5 (based on mineralization of hexane equation)

Based on the assumed porosity and soil bulk density, the term A becomes:

$$A = \frac{0.30}{1,440} = 0.21 \tag{12}$$

The biodegradation rate equation now becomes:

$$K_B[mg\, hexane/kg\, soil/day] = \frac{-K_{O2} \times (0.21) \times (1,330) \times (1/3.5)}{100\%} = 0.8 \times K_{O2} \tag{13}$$

A weakness of this relationship may be its lack of a temperature factor. Equation (13)

shows that there is no direct inference between the biodegradation rate and temperature.

2.5 Soil Characteristics

Soil can be broken down into four phases: soil gases, soil water, inorganic solids,

and organic solids. The gases and water fill the pore spaces and can occupy as much as

50 % of the total volume. The inorganic solids are minerals consisting of silt, sand, and

clay particles (Sims et al. (1989), 2-3). Soil with a higher clay content usually have a

higher moisture content which restricts the diffusion of oxygen. In order to effectively

use bioventing, sufficient soil gas permeability must be demonstrated at the remediation

site. Although soil grain size and soil moisture can influence the diffusivity of oxygen in

soil, excessive soil moisture is perhaps the greatest limitation (Miller (1993), 6).

The US Department of Agriculture defines a soil by the particle size and texture

as shown in the following table (Singer, 4,21,23).

Table 2: Soil Texture, Types, and Particle Diameters

Texture	Type	Particle Diameter
Coarse	Sandy	2.0 to 0.05 mm
Intermediate	Loamy	Mixed with limits of 7 - 27 % clay, 28 - 50 % silt, and 23 - 52 % sand
	Silt	0.05 to 0.002 mm
Fine	Clayey	< 0.002 mm

The clay loams and silty clay loams retain nutrients and inhibit the movement of a contaminant plume better than a sandy soil (Singer, 25). Additionally, the number and types of chemical transformations occurring in the soil are dependent on the amount and types of clay present. Soil with a high clay content have a higher capacity to clean wastes but the oxygen through flow rate is much lower (Singer, 413-414). A soil's porosity controls its behavior with respect to the diffusion of oxygen. The interconnected pores transport water and gases such as oxygen and carbon dioxide (Singer, 42). If a soil is densely compacted, it will have fewer and smaller pores restricting the movement of oxygen and water and inhibiting the convective heat flow. Biodegradation is less likely to occur in compacted soils. Therefore, a balanced mixture of sand, silt, and clay is preferable. Coarse materials like sand and gravel, along with silt, allow oxygen and other nutrients to be transported throughout the site while clay impedes a contaminant's flow. Furthermore, the presence of organic solids typically increases microbial activity leading to a more rapid oxygen depletion (Sims et al. (1989), 7). The soil at the Eielson AFB contamination site is characterized as a sandy and gravely loam with about 10 percent silt in the clay (Hinchee and Ong, 1307).

2.5.1 Soil Temperature

Soil surface temperatures are easily estimated. Numerous studies have shown that the average summer surface temperatures of a vegetation-covered area correlates to the average air temperature. During winter months, this also holds true for the surface of any snow cover. Since snow is a good insulator, it can increase the mean annual ground temperature at the surface by several degrees. Snow has a lower thermal conductivity than dry or wet soil, ice, and rock allowing it to serve as an insulator protecting the soil from further cooling in the winter. At increased depths, the effect on temperature by snow cover diminishes (Johnston, 154-155).

Soil temperatures can vary temporally and spatially. But in order to better understand soil temperature, heat transport in the soil is worth discussing. Convection by water and gases through interconnected soil pores play a minor role in sub-surface temperature changes. Soil temperature is primarily due to the radiant, conductive, and latent energy exchange occurring in the sub-surface. The sub-surface soil is not a simple conducting solid but one that has complex thermal properties with varying layers of soil type, density, and moisture content (Johnston, 149). The following diagram depicts general soil temperature as it varies with depth and season (Smith and Hinchee, 5).
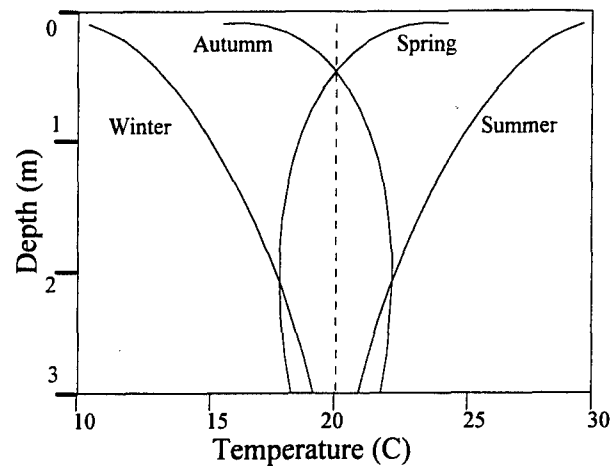
Figure 2: Generalized Soil Temperature Profile

As depicted by the above diagram, changes in sub-surface temperatures are smaller and tend to lag behind that occurring at the surface. In temperate climates, shallow temperatures will be higher in the summer and cooler in the winter than at increasing depths. This lag in temperature change is due to "the difference in coefficients of thermal conductivity and heat convection of the air and the soil" (Jumikis, 45). Heating time of the soil is based on its thermal properties. A soil's thermal properties can be described by its thermal conductivity, heat capacity, and latent heat. These properties vary with soil temperature, phase composition, soil type, porosity, density, organic content, and water content (Johnston, 114).

2.5.2 Thermal Conductivity

Thermal conductivity is defined as the quantity of heat Q flowing through a unit area of a substance of unit thickness in unit time under a unit temperature gradient dT/dz and coefficient of thermal conductivity K of the ground (Johnston, 114).

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$$Q = K\frac{dT}{dz} \qquad (14)$$

Numerous studies have analyzed the relationship between thermal conductivity and numerous soil parameters. Thermal conductivity is higher for frozen soils than unfrozen and increases as the soil's dry density increases. It also increases as soil porosity decreases. Given a fixed dry density, as moisture content increases thermal conductivity will increase at a higher rate (Johnston, 109-111). This relationship also holds for coarse and fine-grained soils. As the volumetric wetness increases from 0.0 to 0.4 for sand with a porosity of 0.4, the thermal conductivity increases from 0.7×10^{-3} to 5.2×10^{-3} cal/cm sec °C. On the other hand, under the same conditions the thermal conductivity of clay will only increase from 0.6×10^{-3} to 3.8×10^{-3} cal/cm sec °C (Smith and Hinchee, 4,6-7). Thermal resistivity, the reciprocal of thermal conductivity, is another indicator of a soil's thermal characteristics and is expressed as 1/°K (Jumikis, 45). In developing plots using the van't Hoff-Arrhenius equation, the biodegradation rate and temperature relationship can be shown by plotting the logarithm of the rate against the thermal resistivity. Conversely, as thermal conductivity increases with higher soil moisture content, thermal resistivity decreases. Resistivity also decreases as soil density increases (Jumikis, 73). The following table shows the thermal conductivity and volumetric heat capacity of various substances (Smith and Hinchee, 7).

Table 3: Thermal Conductivity and Heat Capacities of Selected Materials

Selected Material	Volumetric Wetness	Thermal Conductivity (10^{-3} cal/cm sec °C)	Volumetric Heat Capacity (cal/cm^3 °C)
Sand (porosity = 0.4)	0.0	0.7	0.3
Sand (porosity = 0.4)	0.4	5.2	0.7
Clay (porosity = 0.4)	0.0	0.6	0.3
Clay (porosity = 0.4)	0.4	3.8	0.7
Water (liquid)			1.0
Water (ice)			0.45
Air (dry at STP)			0.00028

2.5.3 Heat Capacity

Heat capacity c is the amount of heat required to raise a unit mass temperature of a substance by one degree where $c = Q/\Delta T$ (Johnston, 115). A soil's heat capacity is dependent upon its mineral and organic makeup, moisture content, and bulk density (Smith and Hinchee, 8). A material's volumetric heat capacity is defined as the amount of heat required to change the temperature of a unit volume of that material by 1 °C (Jumikis, 78). It is accepted that the heat capacity of soil minerals with an assumed density of 2.65 g/cm^3 equals 0.48 cal/cm^3 °C. The organic contained within a soil mineral particle may be natural or contaminant. Natural soil organics have a higher heat capacity, 0.6 cal/cm^3 °C, but a lower density, 1.3 g/cm^3 than the mineral fraction. Comparatively, water has a density of 1 g/cm^3 and a heat capacity of approximately 1 cal/cm^3 °C (Smith and Hinchee, 9).

2.5.4 Thermal Diffusivity

Thermal diffusivity is an index indicating the facility with which a material will undergo a change in temperature (Johnston, 119). Also called the temperature conductivity, it is expressed in units of $[m^2/hr]$ and measures the rate at which a change in temperature α spreads through a body (Jumikis, 73,75).

$$\alpha = \frac{K}{(c_{ms})(\gamma_d)} \tag{15}$$

where K = coefficient of thermal conductivity [Cal/(m)(hr)(°C)]

$\quad\quad c_{ms}$ = mass heat capacity of the soil [Cal/(kg)(°C)]

$\quad\quad \gamma_d$ = dry unit weight of the material [kg/m^3]

There have been few measurements of soils' thermal diffusivities. However, it is known that since the diffusivity of ice is higher than water, hard frozen soils will have a higher diffusivity than thawed soils. Furthermore, coarse grained soils have a higher thermal diffusivity than fine grained ones at a given moisture content level (Johnston, 119). Thermal diffusivity varies widely depending on the levels of air and moisture content present in the soil (Jumikis, 79).

2.6 Soil Temperature in Interior Alaska

As a rule of thumb, the average soil temperature will be approximately equal to the average annual air temperature. Based on 50 years of observation, the mean annual air temperature at Eielson AFB, Alaska, was 26 °F with extreme minimum and maximum

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of -64 °F to 94 °F. The maximum mean daily temperature occurs during June, July, and August with readings of 59, 61, and 56 °F respectively. Conversely, the lowest mean daily temperature occurs in December at -11 °F (Federal Climate Summary). However, by altering the thermal processes on the surface, the sub-surface temperatures can be increased. To do so, incoming solar radiation should be maximized while minimizing surface reflection and radiation. In Alaska, variations in soil temperature is principally "due to annual variations in solar radiation, air temperature, vegetation type, snow cover, and soil properties" (Ping, 1010). Soil temperatures are a "consequence of several interacting factors: kind of plant cover, the soil's moisture regime, evapotranspiration, and weather conditions" (Toogood, 330). To increase a soil's heat adsorption during warm periods and reduce heat loss during cold periods, simple methods such as mulching, surface covers, vegetation, irrigation, and tilling can be performed. These techniques will increase the soil's heat capacity and thermal conductivity and are discussed later.

A soil temperature experiment was conducted at Fairbanks, Alaska, on a barren 10 x 10 meter site free from any vegetation. Thermocouples were buried at 20, 50, 100, 150, 210, 240, and 300 centimeters beneath the surface. Recorded data indicated that the mean soil temperature at shallow depths is closer to the ambient air temperature than at deeper depths. Furthermore, the annual variation at shallow depths vary much more widely similar to the ambient air temperatures. Studies also show that in the arctic "seasonal soil temperature fluctuations do not approximate a simple sine curve" like that occurring in

more temperate latitudes. The temperature curve shows a negative skewness in late spring which increases with depth due to the high saturation right after the spring thaw. The depths at which the maximum temperature occurs increases from July to September. In July, the maximum temperature occurs in the top 50 cm. In August and September, this changes to 40-180 cm and 180-300 cm respectively. The study at Fairbanks also found increasing depths of snow cover have a higher insulatory effect up to a maximum depth of 50 to 60 cm (Ping, 1012-1015).

Efforts to warm the vadose zone may be successful; however, at depths approaching the saturated zone and groundwater make any attempt to increase soil temperature extremely difficult, if not impossible.

2.7 Active Warming Techniques

2.7.1 Heated Air Injection

Hot air injection can raise soil temperature but the heat capacity of injected gases provide only limited application. In order to effectively warm soils, air must be heated to several hundred degrees centigrade. Higher air flows of less warm air is not efficient nor practical as part of a remediation process. However, if hot off-gases were available from a nearby process, e.g., an incinerator, heated air injection may be a reasonable alternative provided the piping distance was minimal. With an extensive network or long piping, heat loss from the air flow will be high. In order to deliver sufficient heat, air temperatures must be above 300 °C which would kill the microbial community near the

injection points. Heating to this high temperature would require heavy piping insulation and a sturdy pipe material such as steel (Smith and Hinchee, 156-157).

In a soil venting field test enhanced by heating, air from an incinerator was injected into the soil to remediate JP-4 jet fuel. Project managers found that hydrocarbon removal increased by 9 percent overall and by 60 percent within the heated area. Researchers calculated that for a soil having a moisture content of 5 %, a dry density of 100 lb/ft^3, and a heat capacity of 0.2 BTU/lb °F, 25 BTUs would be required to raise the temperature of 1 ft^3 of soil by 1 °F. To put this in perspective, one standard cubic foot of air cooling from 1000 °F to 68 °F provides 18.7 BTU. Therefore, to remediate a large volume of soil, extremely hot air must be delivered at a high injection rate in order to elevate soil temperatures (Sittler and Swinford, 40-41). At a similar project injected air was heated to 350 °F and coupled with a soil vapor extraction unit. The in situ cleanup of approximately 7,500 yd^3 cost $90,000 over the project's life span. Comparatively, it is estimated that excavation and landfilling would cost over $500,000 at a cleanup rate of three times faster (Sittler and Swinford, 43).

2.7.2 Heated Water and Steam Injection

As shown later by the Eielson AFB project, another method to actively heat the soil is by warm water injection. As stated earlier, a soil's heat capacity increases with an increasing water content. With a higher heat capacity than air, as warm water migrates through the soil it may provide heat, or it may cool the soil as it evaporates (Singer, 76-

77). Although this convective heating would be more rapid than conduction, it may not be desirable. On the other hand, conduction would take more time allowing the microorganisms to better acclimate to higher temperatures (Dieter, 36). A high moisture content or a site saturated with water can prevent the diffusion of oxygen through the sub-surface and inhibit any microbial activity. In order to maintain the proper moisture content and oxygen level, a site should not be saturated with water (Sims et al. (1989), 7).

The time required to heat the ground to steam temperature will depend upon the injection rate, the volume heated, and the soil characteristics (Dieter, 65). Comparatively, injection of air at 400 °F and a pressure of 10 psi delivers only 1/10 the energy as saturated steam at the same pressure. In order to raise the temperature of unsaturated soil to steam temperature, 100 pounds of condensing steam is required for every cubic yard of soil. Furthermore, steam will heat without saturating the soil because the condensate formed typically does not occupy the entire pore volume. As steam condenses latent heat is released. If the sub-surface soil can absorb this condensate, migration of contaminant transport into uncontaminated zones will be prevented (Dieter, 33,36).

Several projects conducted at naval shipyard facilities have remediated Navy special fuel oil and No. 6 special fuel oil. Managers heated the soil by steam injection which improved contaminant removal rates by enhancing volatilization from the increased vapor pressure. Steam injection enhanced the heavier oil contamination mobility due to viscosity reductions. Project managers stated that steam injection can be used to pretreat a site in preparation for bioremediation by decreasing residual

hydrocarbons. Once complete, the soils are a moist, warm, oxygen-rich environment for microbial activity (Dablow et al., 116).

There are disadvantages to steam injection systems. They require high capital equipment and energy input to produce steam. To inject steam several pieces of equipment are required: a gas-fired water-tubed boiler with feedwater treatment and preheating equipment, piping, insulation, flow meters, and traps (Dieter, 65). Furthermore, the high injection temperatures may adversely affect the biodegradation process (Smith and Hinchee, 44).

2.7.3 Electric Tape

Another soil warming methodology is electric heat tape buried at a shallow depth. To date, except for the Eielson AFB project, there is no known project which employed this type of heating. Much like wrapping water pipes with heat tape to prevent freezing, this technique applies heat without increasing the water saturation at the site. Although the potential electricity costs are high, the faster clean-up results may overcome this disadvantage.

2.8 Passive Warming Techniques

2.8.1 Soil Coverings: Plastic and Fabric Sheeting

Remediation sites are often covered by plastic sheeting to reduce emissions of volatile organic compounds into the atmosphere and prevent contaminant exposure to any

receptors. Covers should be coupled with an oxygen delivery technique since their use can decrease soil aeration and create anoxic conditions. Generally, light-colored covers will reflect heat and prevent excess heating of the sub-surface. Clear plastic tends to act as a greenhouse and heat the soil. It is also reported that black and dark plastic covers will increase heat absorption during the day while reducing heat loss at night which will again increase soil temperature (Baker, 218).

A study showed that soil temperatures increased about 4.5 °C for clear polyethylene covering natural vegetation while an increase of 5.5 °C was realized with clear sheeting over barren soil (Smith and Hinchee, 145). The polyethylene sheeting can become brittle and crack under cold temperatures requiring replacement each summer. The greenhouse effect created by plastic sheeting can be enhanced if the contaminated soil surface is dark in color. Researchers have discovered that under clear plastic a dark colored gravel absorbed more solar radiation and enhanced the greenhouse effect resulting in warmer temperatures (Travis, 5).

Researchers at the United States Army Cold Regions Research and Engineering Laboratory (CRREL) conducted a 30-day field experiment on manipulating soil temperature. These manipulations were designed to be simple and inexpensive in plots of 1 m^2 each located at Hanover, New Hampshire. The researchers classified their passive heating techniques into four categories: 1) plastic ground covers; 2) fabric ground covers; 3) fabric greenhouses; and 4) open-top chambers. The two types of plastic ground covers, black and clear, were cut at a thickness of 0.1 mm and each used with

variations, namely, cutout openings of 25 - 50% of the surface area. The two types of fabric covers, Agronet and Reemay, were also used to act like a greenhouse to trap heat. The fabric greenhouses also used two types of covers, plastic and fabric. Finally, two open-top chambers were constructed to heights of 30 and 60 cm . These chambers were designed to block the convective heat flow transported across the surface by wind. The chambers were expected to provide a day-time heating effect. The experiment showed that the Reemay fabric cover resulted in the maximum temperature increase while the black plastic cover actually decreased soil surface temperatures. The other techniques had temperature responses between these two extremes. Furthermore, the two variations of the clear plastic cover and the Reemay greenhouse were the only other techniques that increased the mean daily temperature by at least 1.0 °C. Marion and Pidgeon were surprised in the results of the black plastic cover. Their theoretical calculations indicated that alteration of the surface albedo would increase soil temperatures. Instead, the black plastic cover produced the opposite effect by decreasing temperatures. Additional research indicated the Reemay fabric cover resulted in the largest temperature increase of the covering techniques. The study concluded that these passive covering techniques can alter the mean daily temperature at the soil surface by at most 2.5 °C (Marion and Pidgeon, 1-8).

2.8.2 Irrigation

Irrigation increases a soil's moisture content yielding a higher thermal conductivity and increasing the heat transfer rate. Irrigation is most effective in sandy soils and least beneficial to soils with a high peat content (Smith and Hinchee, 144). Additionally, irrigation reduces the diurnal soil temperature variation by retaining heat during the nighttime cooler periods (Sims et al. (1986), 130). The amount of irrigation must be balanced against an acceptable level of oxygen diffusion.

2.8.3 Tilling

Soil tilling is a passive technique that alters the sub-surface thermal properties. It not only increases soil aeration but creates a surface mulch which reduces heat transfer between the surface and sub-surface (Sims et al. (1986), 130). Typically, tilling allows for aeration of the top one-foot layer but it can aid in remediation at greater depths. On the other hand, it can dry the soil thus limiting any microbial growth. If tilling is selected as a remediation technique, soil moisture must be monitored and water applied as needed. At contaminated sites in Alberta, Canada, and Palmer, Alaska, tilling was proven to be effective in enhancing biodegradation of crude oil. These projects showed that with increased plow depths, remediation was improved. Coupled with fertilizer applications to overcome nutrient deficiencies, tilling accelerated the recovery of vegetation and plant life (Travis, 5).

2.8.4 Vegetation

To increase soil temperature in the summer, vegetation should be removed since it absorbs solar radiation first (Smith and Hinchee, 143). However, in the winter months a vegetative cover has an insulatory effect and dampens the diurnal fluctuation in soil temperature (Baker, 218). Vegetation maintains a more stable and consistent environment for microbial activity. In one study, removing vegetation increased soil temperatures on average 2 °C (Smith and Hinchee, 145). Vegetation also dampens the annual fluctuations of soil temperature since it acts an insulator throughout the year. At an experimental plot in south central Alaska, grass and fallow cover slowed down the spring and early summer warming at a depth of 10 cm. In fall and winter, this insulatory cover of grass slowed down the cooling appreciably (Ping, 1016).

Mulching has its greatest effect in winter months when it can absorb incoming solar radiation during the day and reduce heat loss at night. It also reduces the diurnal and seasonal fluctuations of soil temperature. Mulches with a low thermal conductivity will reduce heat transfer between the atmosphere and the ground (Sims et al. (1986), 130).

A study conducted at Edmonton, Alberta found that soil temperatures at a depth of 0.20 meters differed by less than 3 °C and less than 2 °C at 1.0 meter under different types of vegetative cover. Overall, grass covered plots had a higher mean annual soil temperature than bare ground or fallowed plots. A vegetative cover was found to insulate

only the top 0.50 meter of soil; therefore, for deeper contamination, it may not be an effective methodology. The study also confirmed the cooling effects of vegetative covers during the summer months (Hayhoe, 62-63,69). Researchers at Edmonton also examined the effect of different vegetative covers on soil temperature at depths of 20 cm and 100 cm. Toogood investigated the thermal characteristics of five different plots: 1) fallowed plot, 9 m x 9 m - barren and free of vegetation; 2) barley plot, 9 m x 9 m - crop seeded in mid-May and harvested in August; 3) shrub plot, 9 m x 9 m - clumps of western strawberry shrubs covering the plot; 4) deciduous tree plot, 18 m x 18 m - aspen poplar saplings spaced 1 m apart; 5) coniferous tree plot, 18 m x 18 m - white spruce trees spaced 1 m apart. Temperature readings were taken at the center of each plot. During the winter, soil temperatures at 20 cm were highest for the shrub plot and lowest for the barley but were determined to be a function of snow cover depth. In the summer months, the fallowed and barley plots had higher soil temperatures (Toogood, 329-330). By early April, temperatures in all plots were nearly the same. At 100 cm, the spread of soil temperatures among the plots narrowed and all plot temperatures were within 1 °C of each other and mirrored the results found at the 20 cm depth (Toogood, 335).

2.8.5 Composting

Also called a biopile, composting is considered an aboveground treatment. It could be a technique to warm the sub-surface. A layer of compost can provide an insulatory barrier while generating heat from microbial activity. This passive warming

technique is only effective if the layer of composting is kept organic-rich and turned over on a frequent basis to allow aeration and prevent compaction. There have been several studies on temperatures in a compost pile. At a site in Quebec, Canada, the average winter pile temperatures never decreased below 7 °C despite ambient temperatures below -20 °C. Furthermore, the pile never froze with its surface temperature at the coldest months only dipping to 4 °C (Samson et al., 331). In a biopile study recently conducted by Benazon and others, both temperature and oxygen levels were measured in an active and passive aeration system. In the passively aerated biopile, oxygen was transferred through pipes installed at the base and intermediate depths by diffusion and free convection. At the actively aerated biopile, blowers injected oxygen from blowers and a network of piping. Researchers found the active biopile had slightly higher temperatures initially and oxygen levels more consistently distributed. They concluded that despite lower costs with the passive biopile, oxygen diffusion was limited to shallow depths, less than 0.8 m; therefore very little remediation was observed at larger depths (Benazon et al., 179-190). In order to be an effective soil warming treatment, composting should be coupled with an air injection technique like bioventing.

2.8.6 Solar Energy

A project being conducted at Hill AFB is examining the effectiveness of capturing solar radiation in order to further warm the soil. One sample plot has a 5 ft by 5 ft plywood box frame constructed over it. The frame holds a single-pane glass sheet titled

at 38° to 40° to maximize the capture of solar energy. The glass sheet is mounted 6 in above the ground allowing space for a heat retention system and instrumentation to measure environmental conditions. Another plot is constructed similarly but with the addition of an artificial heating system to maintain elevated air and soil temperatures throughout the 1-year study period. The project was expected to be complete in the summer of 1995 but results have not been made available (Montgomery Watson, 6-7).

2.9 Case Studies on Contamination in Subarctic Environments

There are many remote sites in Alaska contaminated from bulk storage releases of fuel oil. Remediating these remote sites, some under extremely cold conditions, can be very expensive. Without enhancing petroleum spill remediation, the arctic tundra and subarctic forest soil may be affected for up to 30 years since intrinsic bioremediation is impeded by the cold climate and short growing season. Like most soils, microbial abundance in the arctic declines at increasing soil depths due to lower availability of oxygen, nitrogen, phosphorous, and warmer temperatures (Travis, 4). Arctic soil does not thaw sufficiently to allow bioremediation until June. In remote arctic locations, such as the North Slope, soil temperatures peak in mid-July at about 7 °C. The window of opportunity for microbial activity closes at about the end of September when the soil begins to freeze. Therefore, a treatment like bioventing may be an alternative if the constraints of low temperatures can be overcome (Brar et al., 127). Prior to 1991 and the

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start of the Eielson AFB project, the success of bioventing had not been demonstrated in a cold environment.

A site contaminated with 12,600 - 25,200 gallons of crude oil at the Kuparuk Oil Field, Alaska, was remediated in situ. Located at Alaska's North Slope the site has no roadway access and any remediation activity is dependent upon barges to deliver equipment and supplies. This restriction is not uncommon for many areas of Alaska. Project managers discovered that stimulating hydrocarbon degradation was most effective by removing snow early to promote early warming, pumping snowmelt water to allow air infiltration, and adding lime to increase the pH. Within 3 years, the total petroleum hydrocarbons had decreased from 16,000 mg/kg to less than 1,600 mg/kg (Fredrickson, 1714).

Another bioremediation site was Point Thomson located at Alaska's northern extreme approximately 100 miles east of Kuparuk. There, ambient temperatures ranged from 30 to 46 °F in the summer and -20 to -6 °F in the winter. In 1989, samples indicated diesel contamination of 3,000 ppm TPH underneath a gravel pad. Since the short summer lasts a maximum of 8 to 10 weeks with soil temperatures at about 41 °F, the lag time for microorganism acclimation may take several days to two weeks. Preliminary laboratory assessments showed that bioremediation could be an effective treatment. They found that the percentage of petroleum degrading microorganisms at the site ranged from 0.7 to 61.1 % of the total number present. The site was characterized as nutrient-limited with a pH of 8.7. Based on laboratory results, project managers decided to apply a

nutrient and microbial cultured solution. Measurements taken in 1990, the first remediation season, indicated that the microbial population increased by an average of 1 to 1.5 orders of magnitude while TPH concentrations decreased by an average of 36 %. Over three seasons, TPH concentrations were reduced by 80% from 1,419 to 286 ppm. Although the 200 ppm cleanup guideline of the Alaskan regulatory agency was not met, the results demonstrated that bioremediation accelerated microbial degradation of the diesel contaminant (Liddell, 132-136). More importantly, the project demonstrated that bioremediation can be effective in arctic environments.

Another remediation project conducted at a remote military base located at Shemya, Alaska, demonstrated the effectiveness of biodegradation at low temperatures using an ex-situ bioventing design. Two aerated biopit remediation cells were constructed to treat contaminated soil with an air flow rate ranging from 19 to 30 ft³/min. The experiment included a fertilized and nonfertilized treatment lasting 148 days with ambient temperatures ranging from -3 to 6 °C. The total volume of diesel fuel contamination was unknown but estimated to be much greater than 67,000 gallons. Temperature measurements were taken hourly by an automatic data logger at four different depths at four locations in each treatment cell. Results showed that temperatures in the fertilized treatment cell were higher than the nonfertilized cell and the ambient conditions. Additionally, the minimum temperature of the fertilized cell over all depths was always greater than the maximum temperature at any depth of the nonfertilized cell. The data also showed that the injected ambient air has a cooling effect and indicated that

convective cooling effects were not spatially biased. With an initial TPH level of 1304 mg/kg, the fertilized cell satisfied the Alaskan DOE Conservation guidelines of 200 mg/kg of diesel-range petroleum hydrocarbons in less than 115 days. On the other hand, the nonfertilized cell had not satisfied the cleanup target level after 148 days (Brar, 127-130). This project demonstrated that bioventing can successfully work in cold climates but nutrients may be required in order to reduce remediation time.

CRREL has performed extensive research on the fate and effects of crude oil spilled in subarctic climates. Two experimental spills of Prudhoe Bay crude oil were conducted in February and July 1976 at a research watershed 48 km north of Fairbanks, Alaska. The spill sites were studied intensively prior to and for three years following the spill. It was also revisited in 1990 "to assess the long-term effects on permafrost and vegetation, as well as long-term changes in oil chemistry." In 1978, Collins and others noted increased microbial activity in those areas where oil concentration had been extremely high. At the spill performed during the winter, oil contamination did not migrate as far as the summer spill and had less oil spreading into the sub-surface. Permafrost for the area was defined as discontinuous but measurements taken at an undisturbed control plot showed permafrost at 57 cm. Comparatively, permafrost at the spill site had increased to among 70 and 88 cm (Collins et al., 1-3). The study also demonstrated that weathering of the oil resulted in the loss of volatiles (C_5 - C_9) first. Researchers detected no volatiles 17 months after the spill but, they were still detectable in the organic and mineral soils. Even 15 years later, volatiles were still detectable which

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was unexpected but likely attributed to the low flux of air. This is indicative of the persistence of an oil spilled on soils underlain by permafrost (Collins et al., 9,17). Furthermore, it was determined that surface soil samples had degraded more than subsurface samples. This suggests that the warmer surface temperatures and aerobic conditions allow microbiological activity to change the composition of the oil contamination and is conducive for the presence of oil-degrading bacteria. The authors also agree "that bioremediation techniques could be used to enhance natural biodegradation in this type of setting if the factors limiting microbial activities are ameliorated" (Collins et al., 17).

Permafrost is defined as frozen soil with temperatures below 0 °C persistently over at least two consecutive years. In the zone above the permafrost, high soil moisture is present in the seasonally thawed layer just beneath the surface and is called the active layer. Permafrost impedes soil drainage creating an impermeable barrier and underlies approximately 80 % of Alaska. Increasing the permafrost depth or melting it will have a significant impact on any industrial or human activity in the area. Thermal degradation of permafrost leads to erosion of the frozen soil creating unstable soil layers (Johnston, 21,31). The unstable soil layer is manifested as a soil flow or landslide resulting in the removal of the insulating vegetative cover and the toppling of trees (Johnston, 62-63).

Damage to the permafrost was a primary concern to project managers trying to remediate a remote USAF station under harsh conditions and located above the Arctic Circle. The site is located approximately 610 miles northwest of Anchorage along the

coastline. In 1984, a ruptured diesel fuel pipeline contaminated a tundra hillside covering two acres. Very little recovery of vegetation had been noted in 1989 when project managers considered tilling as an active bioremediation approach to clean up the site. Due to the likelihood of damaging the underlying permafrost, they decided to passively remediate the site (Piotrowski et al., 115-116). Two approaches were selected. One technique was landfarming where the contaminated soil was excavated, replaced with clean fill, and biologically treated in a lined land treatment unit. The second technique employed was a surfactant application. The surfactant included a solution of nutrients that would enhance microbial activity. Project managers felt that application of a non-toxic, biodegradable surfactant would render residual contamination more accessible to microorganisms since organic compounds generally degrade in the aqueous phase (Piotrowski et al., 119,122). The time frame for remediation success was limited between May and September of each year because freezing temperatures reduced microbial activity and prevented many operations from occurring. During the period, August 1989 through September 1990, the overall reduction in TPH concentration with the landfarming technique was approximately 75% (Piotrowski et al., 136). On the other hand, the surfactant technique was not effective in reducing TPH concentrations.

This literature review has demonstrated the efficacy of bioremediation in colder climates like Alaska. Although it is primarily a seasonal operation limited to the summer months when ambient conditions are conducive, engineered bioremediation can extend in situ conditions allowing microbial degradation of contaminants to occur in the colder

months. Bioventing applications under these conditions have also been demonstrated. This research is illustrated by the project focused in this thesis and discussed in the next section.

III. Project Design and Methodology

3.1 Site Description

Eielson AFB is an active US Air Force base located at 64° 40'N and 147° 6'W, approximately 25 miles southeast of Fairbanks, Alaska in the Alaskan Interior. At an elevation of 561 ft, the climate at Eielson AFB is considered sub-arctic with an average annual temperature of 0 °C. Temperatures range below -30 °C to above +30 °C. Within the base's fuel distribution network, a JP-4 jet fuel spill occurred near an active runway. Soil at the contamination site is primarily glaciofluvial deposits and is characterized as interbedded layers of loose sand and grave with silt concentration increasing to a depth of 2 meters. The area is marked by discontinuous permafrost but it does not occur in the vicinity of the contaminated site. The groundwater table at the base measures between 5 and 15 ft. Within the area of the bioremediation project, "the groundwater level is at approximately 9.5 ft near the background and 7 ft in the contaminated area." Additionally, the underlying sole-source aquifer has a few zones of contamination (Leeson et al., 285-288).

The total surface area of the bioventing remediation effort is approximately 1 acre including the background area and shown by the following drawing (Figure 3). Oxygen was injected at rates between 2.5 - 10 ft^3/min. All plots were thermally isolated from the adjacent test plots by a minimum spacing of approximately 30 feet. The active and passive warming plots were insulated with Styrofoam™ while the control plot was not.

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In addition, an uncontaminated and unheated background plot was located about 200 feet

from the test site (Leeson et al., 288).
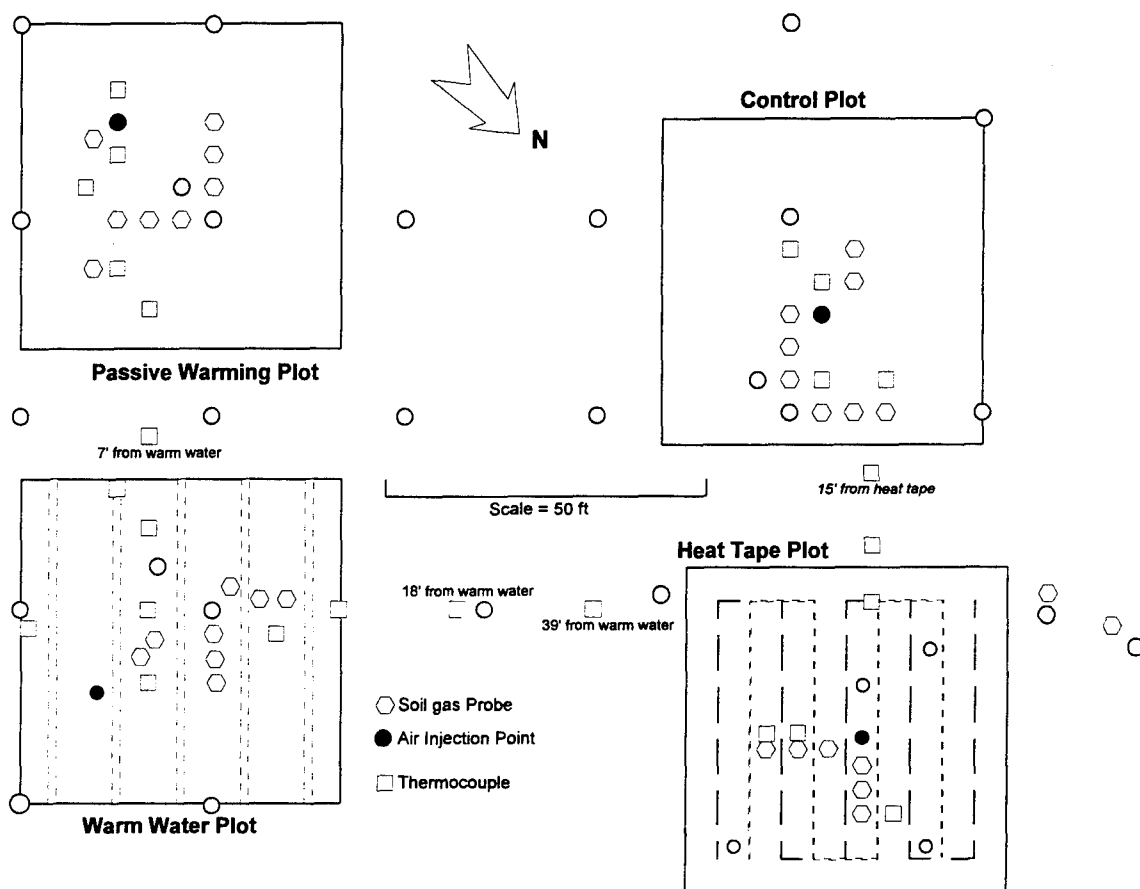
Figure 3: Eielson AFB Remediation Site

3.2 Site Contamination

Samples of soil, soil vapor, and groundwater indicated significant concentrations

of hydrocarbons. Soil samples showed more the common contaminants as n-octane, n-

dodecane, n-heptane, and toluene. In soil vapor samples, 2,4-dimethylpentane, 2-

methylpentane, benzene, n-heptane, n-hexane, and toluene were most common with

higher concentrations present in the warm water and passive warming plots as shown by

Table 4 (Battelle, Appendix K-1). One of the project managers, Dr. Gregory Sayles, stated that contamination levels were lower in the warm water plot (Personal Communication).

Table 4: Distribution of Contaminants in Soil Gas Samples in August 1991

Compound	Concentration (ppmv) at Location								
	A1A	P2A	P4A	P5A	P6A	ATM2'	ATM4'	ATM6'	Bkgd
Total C_5-C_{15}	29750	11503	1567	30782	<0.080	46	<0.080	<0.080	<0.080
Total C_6	30000	11599	1580	31039	<0.080	48	<0.080	<0.080	<0.080
Benzene	402	678	32	808	<0.005	7.02	<0.005	<0.005	<0.005
2,4-Dimethylpentane	2055	1441	159	2906	<0.007	7.19	<0.007	<0.007	<0.007
Ethylbenzene	18.48	6.01	<0.004	18	<0.004	<0.004	<0.004	<0.004	<0.004
n-Heptane	1335	526	83	1665	<0.005	6.14	<0.005	<0.005	<0.005
n-Hexane	3718	<0.005	276	3078	<0.005	10.4	<0.005	<0.005	<0.005
2-Methylpentane	2830	2060	181	3684	<0.007	<0.007	<0.007	<0.007	<0.007
n-Octane	406	67	21	464	<0.004	<0.004	<0.004	<0.004	<0.004
n-Pentadecane	<0.004	0.23	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Toluenes	227	296	35	778	<0.003	2.2	<0.003	<0.003	<0.003
p-Xylenes	60	<0.003	<0.003	45	<0.003	<0.003	<0.003	<0.003	<0.003

Description of Locations:

A1A	Warm water plot probe at depth of 5.25 ft
P2A, P4A, P5A, and P6A	Passive warming plot probes all at a depth of 5.25 ft
ATM2', ATM4', ATM6'	Ambient air samples at 2, 4, and 6 ft above the site
Bkgd	Background (uncontaminated) area

Additionally, groundwater samples showed significant concentrations of total hydrocarbons. Initial TPH contamination levels in groundwater are reflected in the following table (Battelle, 15,19).

Table 5: TPH Contamination in Groundwater Samples, August 1991

Background	Extraction Well	Warm Water	Passive Warming	Control
<0.0002 mg/L	20 mg/L	17 mg/L[1]	15 mg/L[1]	15 mg/L[1]

[1]Average of two samples.

Before the project began, laboratory studies isolated hydrocarbon degrading microorganisms and demonstrated degradation at temperatures ranging from 2 °C to 20 °C. Compared against a control column of soil, researchers discovered that as the temperature increased to 20 °C, the production of CO_2 was much greater with the Eielson soil sample. This suggested that the indigenous microorganisms were adapted to the colder climate and that their natural metabolic rate was comparable to those organisms found in more temperate climates. Based on the laboratory results, field studies were initiated (Leeson et al., 290).

3.3 Soil Warming Methodologies

3.3.1 Warm Water (Active Warming) Plot

The warm water plot at the Eielson AFB site is referred to in published articles as the active warming plot. The site map is shown in Figure 4. Plot details are described below (Battelle, 24,26):

- Four shallow bioventing wells installed in 1991.
- One deep bioventing well installed in 1992.
- Within the plot, four sets of "A" thermocouples measuring temperatures at depths of 5.25, 4.25, and 2.0 ft installed in 1991.
- Two sets of "B" thermocouples measuring temperatures at depths of 6.0, 4.0, and 2.0 ft installed in 1992.

- One thermocouple located at the end of a trench measuring the temperature next to the soaker hose at a depth of 2.0 ft.

- Six sets of soil gas monitors installed in 1991 at depths of 5.25, 4.25, and 2.0 ft.

- Two sets of soil gas monitors installed in 1992 at depths of 7.5, 4.5, and 2.5 ft.

- One groundwater well for the supply and return of water circulating through the soaker hoses buried in perforated PVC pipe.

- Surface area covered by Styrofoam™ insulation to retain heat.

Figure 4: Warm Water Plot

7' from plot

19-21
5.25, 4.25 & 2'

on soaker hose (2.5 ft)

40 B

16-18
5.25, 4.25 & 2'

W

5.25, 4.25 & 2'
S4

5.25, 4.25 & 2'
S5   S6

On border

5.25, 4.25 & 2'
4-6

5.25, 4.25 & 2'

7-9
5.25, 4.25 & 2'

25-27
6, 4 & 2'

7.5, 4.5 & 2.5'
S7

S3
5.25, 4.25 & 2'

22-24
6, 4 & 2'

7.5, 4.5 & 2.5'
S8

S2
5.25, 4.25 & 2'

1-3
5.25, 4.25 & 2'

S1
5.25, 4.25 & 2'

Scale = 10 ft
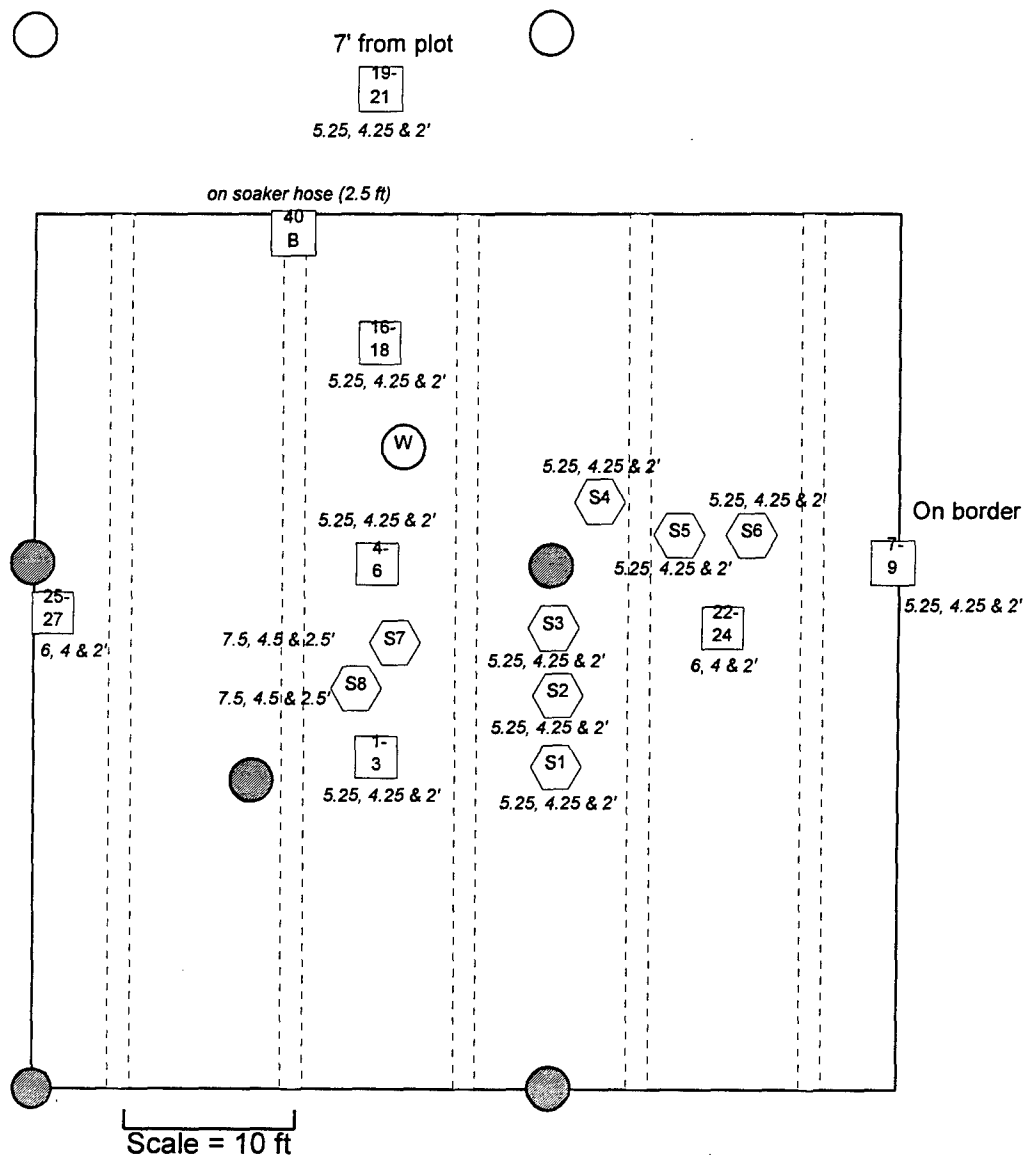
⬤ Air Injection Point   Ⓦ Groundwater Monitoring

☐ Thermocouple   ⬡ Soil gas Probe

*On this and the following maps, thermocouples numbers separated by a hyphen are inclusive, e.g., 16-18 indicate thermocouple numbers 16, 17, and 18.
**Two additional sets of thermocouples, 10-12 and 13-15, are located 18' and 39' right of thermocouples 7-9.

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The plot is characterized by five 50 ft length trenches at depths of 2.5 ft and spaced 10 ft apart. Two 50 ft lengths of soaker hoses were placed inside perforated PVC sewer pipes and buried along the length of the trenches. The soaker hoses were linked to form a loop and protected from freezing by heat tape in the sewer pipes. Water was pumped from a well at the site and circulated through the loop of soaker hoses. The water volume was controlled by the use of gate valves and heated by three in-line instantaneous water heaters connected in parallel. The pumped water volume "injected into the site was increased when the pressure on the soaker hoses was increased." The system operated under a general pressure of 25-30 psi. The water pump, heaters, and extraction well were installed beneath the surface to prevent contaminated groundwater from reaching the surface (Battelle, 24,26,Appendix B-9). The water was heated to approximately 35 °C and about 1 gal/min of water was released into the subsurface dispersion manifold. Active heating of the plot did not begin until October 1991 (Leeson et al., 289,291). Water heating and circulation continued until July 1993 when the system was turned off and insulation removed. This was done in order to provide a comparison of microbial activity without heating (Battelle, 22).

3.3.2 Passive Warming Plot

Designed to maximize solar warming, the passive warming plot promoted soil warming with different coverings, depending on the season. The plot was covered by black landscaping cloth with clear plastic added during the spring and summer. During

winter months, the plot was covered with Styrofoam™ insulation and a nylon tarp secured

by ropes and boards. During the second year, black weed stopper was placed underneath

the clear plastic to reduce plant growth. Shown in Figure 5, the plot is described in detail

below (Battelle, 26,Appendix B-11):

- Four shallow bioventing wells installed in 1991.
- One deep bioventing well installed in 1992.
- Three sets of "A" thermocouples measuring temperatures at depths of 5.25, 4.25, and 2.0 ft installed in 1991.
- Two sets of "B" thermocouples measuring temperatures at depths of 6.0, 4.0, and 2.0 ft installed in 1992.
- Six sets of soil gas monitors installed in 1991 at depths of 5.25, 4.25, and 2.0 ft.
- Two sets of soil gas monitors installed in 1992 at depths of 7.5, 4.5, and 2.5 ft.
- One groundwater monitoring well.
- Surface area covered by Styrofoam™ insulation to retain heat.

Scale: 1 inch = 10 feet

⬤ Air Injection Point   (W) Groundwater Monitoring

☐ Thermocouple   ⬡ Soil gas Probe
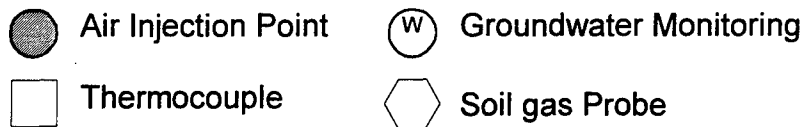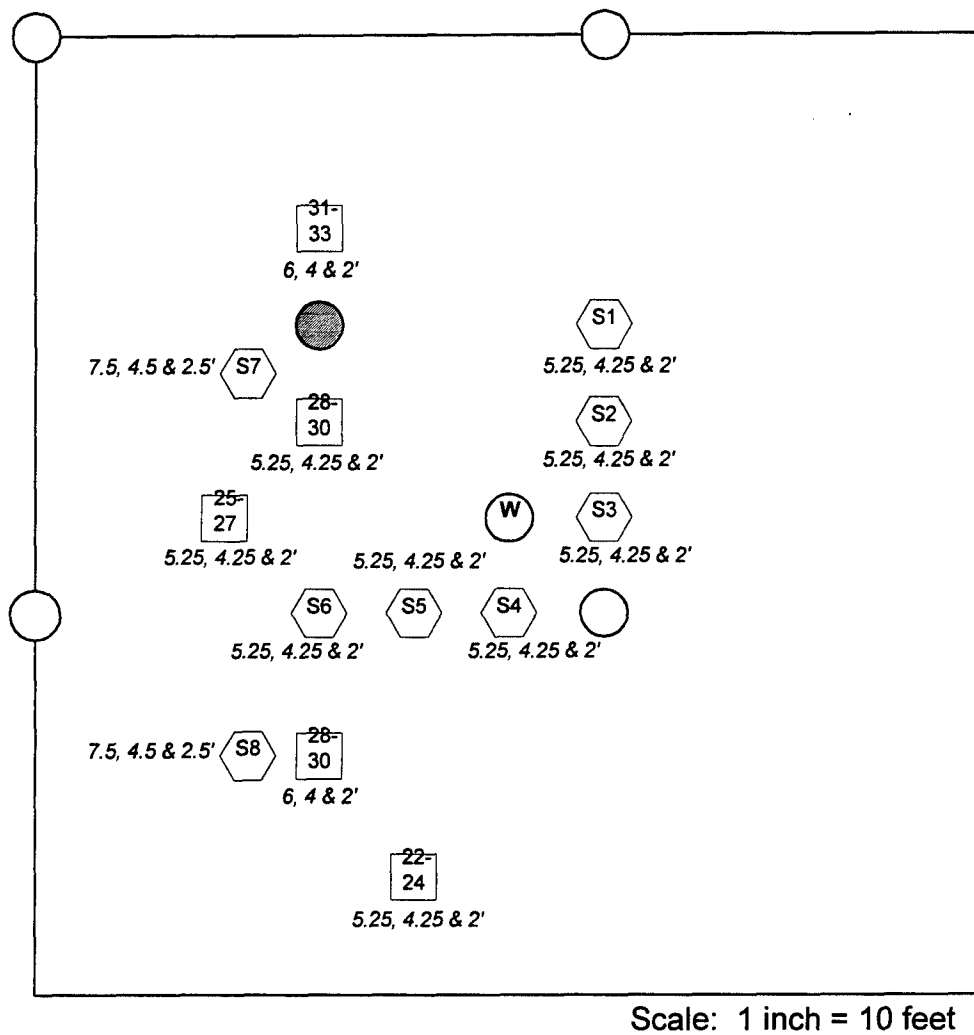
Figure 5: Passive Warming Plot

3.3.3 Control Plot

The control plot was constructed in order to provide a comparison against an

untreated contaminated plot. Similarly, air was injected at the plot but no surface covers

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were utilized during the treatment period. Shown in Figure 6, the plot is described in

detail below (Battelle, 29):

- Four shallow bioventing wells installed in 1991.

- One deep bioventing well installed in 1992.

- Two sets of "A" thermocouples measuring temperatures at depths of 5.25, 4.25, and 2.0 ft installed in 1991.

- Two sets of "B" thermocouples measuring temperatures at depths of 7.5, 4.5, and 2.5 ft installed in 1992.

- Six sets of soil gas monitors installed in 1991 at depths of 5.25, 4.25, and 2.0 ft.

- Two sets of soil gas monitors installed in 1992 at depths of 7.5, 4.5, and 2.5 ft.

- One groundwater monitoring well.

Scale: 1 inch = 10 feet

Air Injection Point   (W) Groundwater Monitoring

☐ Thermocouple   ⬡ Soil gas Probe
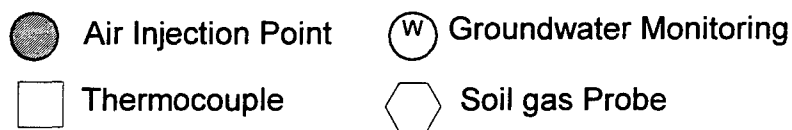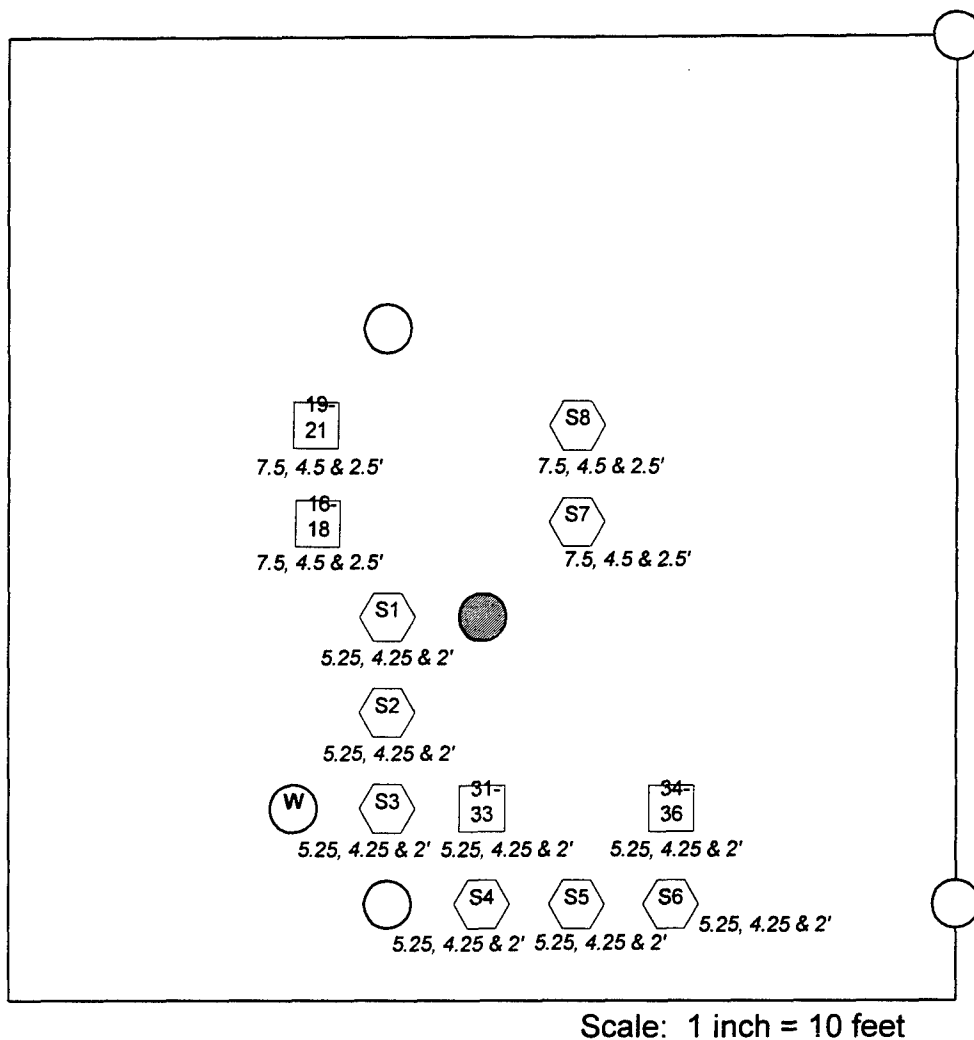
Figure 6: Control Plot

3.3.4 Heat Tape (Surface Warming) Plot

This plot is referred to in published articles as the surface warming plot. It was

installed in September 1992 after being funded by the EPA. This heating technique

provides another warming comparison. Shown in Figure 7, the plot is described in detail

below (Battelle, 29,32):

- Four shallow bioventing wells installed in 1992.

- One deep bioventing well installed in 1992.

- Within the plot, three sets of "B" thermocouples measuring temperatures at depths of 7.5, 4.5, and 2.5 ft installed in 1992.

- One "B" thermocouple located at the end of a heat tape row measuring the adjacent temperature at a depth of 3.0 ft.

- Six sets of soil gas monitors installed in 1992 at depths of 7.5, 4.5, and 2.5 ft except for point #4 installed at depths of 7.0, 4.0, and 2.0 ft.

- Surface area covered by Styrofoam™ insulation to retain heat.

13-
15

6, 4 & 2' (15' outside of plot)

10,
11

6 & 4'

12

3.0' (near heat tape)

S7

S8

7.5, 4.5 & 2.5' *7.5, 4.5 & 2.5'*

1-
3

4-
6

S1 S2 S3 *7.5, 4.5 & 2.5'*

7.5, 4.5 & 2.5' *7.5, 4.5 & 2.5'*

S4 *7, 4 & 2'*

S5 *7.5, 4.5 & 2.5'*

7.5, 4.5 & 2.5' S6

7-
9

7.5, 4.5 & 2.5'

Air Injection Point

Thermocouple

Soil gas Probe

Scale = 10 ft
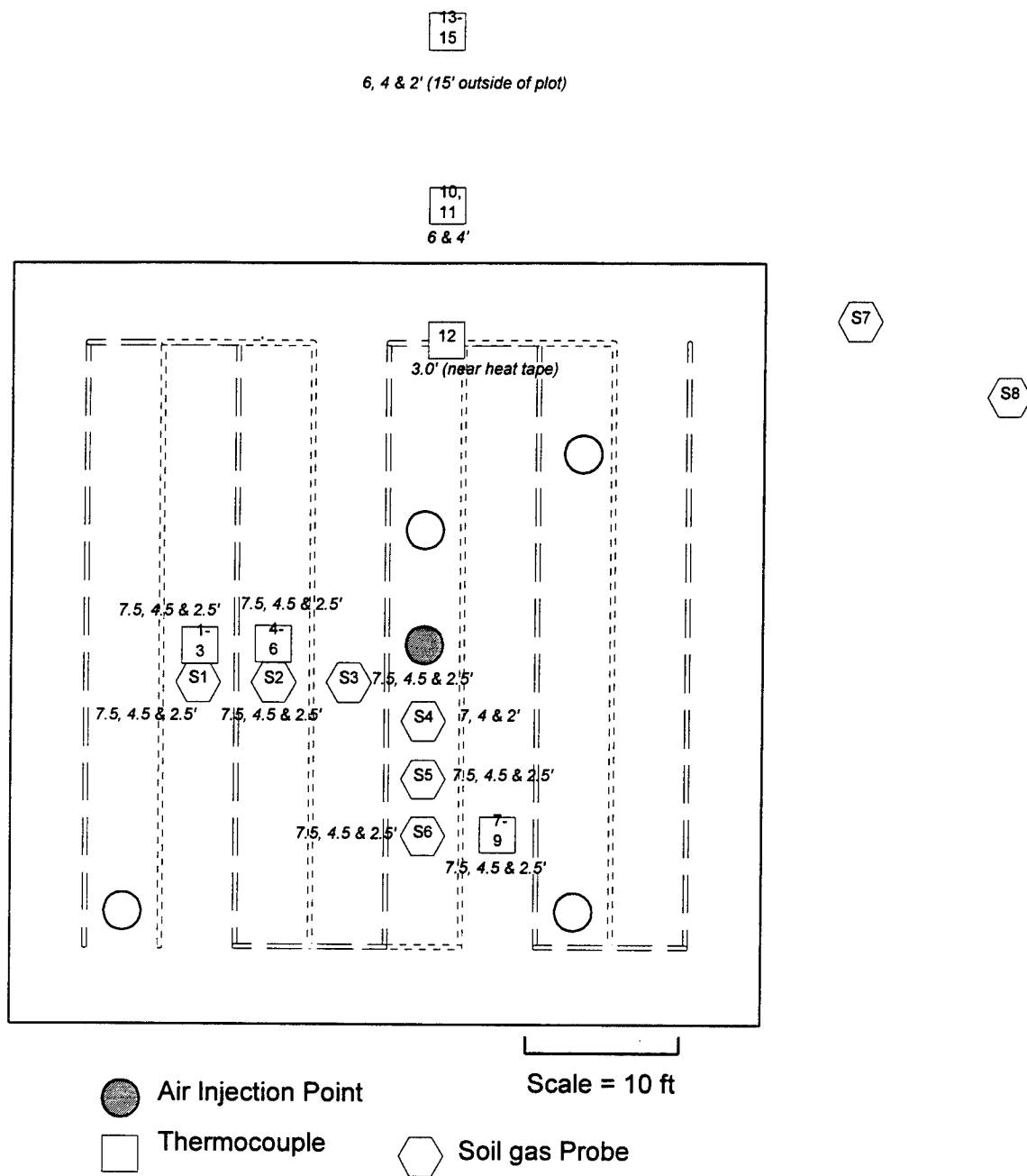
Figure 7: Heat Tape Plot

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Two overlapping strips of heat tape were installed at a depth of 3 ft in a serpentine fashion in nine rows 5 ft apart with the first and last rows 5 ft from the border. The overlapping strips were powered separately to allow one strip to be disconnected if soil temperatures rose too high. Each row of heat tape terminated 5 ft from the edge of the plot (Battelle, 32). The strips of heat tape provide a heat rate of 5-6 W/ft with a total heat load to the plot of about 1 W/ft^2 (Sayles et al. (1994), 146).

3.3.5 Perimeter and Background Area

Additional thermocouples were installed along the perimeters of the four contaminated plots. Outside of the heat tape plot, two soil gas probes were installed. Additional soil gas monitoring points were established throughout the entire site to monitor O_2 concentrations. An uncontaminated background area was located approximately 200 feet southwest of the site. Two soil gas monitoring points and a three-level thermocouple were installed there. One soil gas monitor was buried at a depth of 3.5 ft with the other probe monitoring three depths: 2.5, 4.5, and 7.5 ft. Additionally, the background area was not insulated (Battelle, 32).

3.4 Bioventing System Design

Installed in 1991, the spacing and placement of the bioventing wells were designed on a conservative assumption that the effective radius of influence for oxygen injection was only 15 ft. The configuration of the soil warming plots and the sampling

objectives also helped determine the location of the wells. Four wells located 30 ft apart

were installed to allow for adequate and uniform aeration of the individual test plots.

This spacing ensured that soil temperature was the only characteristic varying between

the plots. After a year of operation, a fifth vent well was installed at the center of each

test plot (Battelle, 43). Following air permeability tests at the plots, radius of influence

calculations showed an average radius of 61 ft at the 6 ft depth. The radius of influence

ranged from "40 ft for the passive warming plot to 77 ft for the surface warming test

plot." As a result of the permeability tests, the project managers concluded that a

bioventing well spacing of 80 ft may be sufficient to cover the site. Furthermore, to treat

the 1 acre site, approximately 9 wells would be required (Battelle, 72,75). The project

managers used this information and turned off the initial four vent wells. "Except for the

warm water plot, the test plots required only one injection well in operation to meet

oxygen demand" (Sayles et al. (1995), 300).

3.5 *Soil Gas Sampling and In Situ Respiration Testing*

Soil gas sampling was conducted approximately on a weekly basis. On numerous

occasions, high soil moisture content prevented sampling from some soil gas monitoring

points (Battelle, 51). This weekly soil gas data is not presented nor analyzed as part of

this thesis effort. Instead, the O_2 consumption data calculated from the in-situ respiration

tests is analyzed to determine biodegradation rates occurring at the site. As discussed

earlier, the principal measure used for monitoring microbial activity at bioventing sites is

an in situ respiration test. This test measures oxygen depletion and takes about 5 to 7 days to complete. After turning off the air injection, changing levels of O_2 in the soil gas are then monitored. Like most tests, any results should be compared to background monitoring points. At Eielson AFB, background monitoring points showed that the effective microbial oxygen consumption was zero.

At the Eielson AFB project, abbreviated in situ respiration tests were conducted every 30 to 60 days. These abbreviated tests involved a partial sampling of the soil gas probes. Approximately every three months, full in situ respiration tests were performed with samples attempted at all probes. From the available oxygen consumption data, linear regressions were performed to calculate a slope in units of *[% O_2/hr]* for each soil gas probe depth and individual test. It was assumed that the slope indicates the rate that indigenous microorganisms consume oxygen. Therefore, a positive slope is not feasible since this would indicate the production of oxygen. Only those slopes that are approximately zero or negative are acceptable. In performing linear regressions, an R^2 value of 0.45 was selected as the minimum acceptable for analysis. At the passive warming and control plot, nearly all R^2 values were greater than 0.90. But, for the warm water and the heat tape plots, a lower acceptable R^2 value was required in order to have sufficient data to analyze. The lower R^2 values obtained from these two actively warmed plots suggest the following possibilities: 1) environmental conditions in the soil prevented a linear decay of oxygen; 2) another variable, such as soil moisture, changed the assumed oxygen consumption relationship from a zero order to a higher order one or

a discontinuous regression; 3) environmental conditions made it difficult to take accurate samples; or 4) the warm water and heat tape plots were not identical or similar to the control and passive warming plot, e.g., they were positioned downgradient or the underlying soil characteristics were much different.

3.6 Temperature Data Paired with Oxygen Consumption Data

Soil temperature measurements were recorded automatically two to three times daily with an automatic data logger. Data points taken every two to four days are available in the appendices of the project report written by Battelle and others. To determine the true biodegradation rate occurring at each soil gas probe and depth, temperatures at a point in time were paired with the corresponding oxygen consumption rate for the same time period. Determination of temperatures at a specific location for each plot are detailed below. In determining temperatures, it was assumed that soil layers were homogeneous at a particular depth. When temperature data was unavailable for the middle depth range, an average between the shallow and deep depths was taken. If data was unavailable at the other depths, deep or shallow, it was estimated from the nearest thermocouple at the same depth. The paired temperature values are shown in Appendix C with the calculated oxygen consumption rates. Details on the determination of temperatures is given below.

3.6.1 Warm Water Plot Temperature Derivation

It is assumed that within this plot the soil temperature gradient between each row of warm water soaker hoses was identical to other rows at the corresponding depth. However, due to the decreasing water temperature from the point of injection, linear interpolations were performed along a parallel of the hoses. The interpolations utilized available temperature data, whether thermocouples were located between the same hoses or not. Located at the same y-coordinate, temperatures from thermocouples 1A-3A were used to estimate that present at the matching depths of soil gas probe 1. Temperatures at soil gas probes 2 and 3 were linearly interpolated between thermocouples 1A-3A and 4A-6A. For soil gas probes 4, 5, and 6, temperatures were interpolated between thermocouples 4A-6A and 16A-18A with data at matching depths. Temperatures at soil gas probes 7 and 8 were interpolated between thermocouples 1A-3A and 4A-6A.

3.6.2 Passive Warming Plot Temperature Derivation

Since no active heating was performed at this plot and, based on the principal assumption of site homogeneity, it was assumed that soil temperatures were constant throughout the plot at a particular depth. Thermocouples 22A-24A, 25A-27A, and 28A-30A were installed at the same time and at the same depths as soil gas probes, 1-6. Temperature measurements at these locations were averaged by depth and used as an estimate for the corresponding soil gas probe depth at that point in time. Thermocouples 28B-30B and 31B-33B were installed at the same time as soil gas probes 7 and 8 but not

at matching depths. Nevertheless, temperatures from these thermocouples were also averaged and matched according to depth with the corresponding oxygen rate data because these later thermocouples were installed deepest at the plot.

3.6.3 Control Plot Temperature Derivation

Since there was no active heating or disruptive installation activity, it was assumed that soil temperature was constant at all depths throughout this plot. This assumption is identical to that applied at the passive warming plot. Since thermocouples 31A-33A and 34A-36A were installed at the same time and the same depths as soil gas probes 1-6, temperature measurements for these points were averaged by depth and used as an estimate for the corresponding soil gas probe depth. Similarly, thermocouples 16B-18B and 19B-21B were installed at the same time and the same depths as soil gas probes 7 and 8. Temperatures from these thermocouples were also averaged and matched according to depth with the oxygen rate data corresponding in time.

3.6.4 Heat Tape Plot Temperature Derivation

Identical to the warm water plot assumption, the soil temperature gradient between each heat tape row is assumed to be identical across the plot at corresponding depths. Linear interpolations at each depth were performed along a parallel of heat tape rows. The interpolations utilized available temperature data, whether thermocouples were located between the same tape rows or not. Temperatures from thermocouples 1B-

3B estimate those occurring at soil gas probe 1 since they are located at identical depths and next to each other. The same holds true for thermocouples 4B-6B and soil gas probe 2. Temperatures estimated for soil gas probes 1 and 2 were averaged and assumed for those occurring at soil gas probe 3 since these probes were located along the same Y-coordinate. Temperatures at soil gas probes 4 and 5 were linear extrapolated between thermocouples 4B-6B and 7B-9B. For soil gas probe 6, temperatures were estimated from thermocouple 7B-9B since they are both located at the same Y-coordinate. During some in situ respiration tests, temperature data was unavailable for thermocouple 4B; therefore, thermocouple 1B was the data estimate.

3.7 Data Analysis Approach

Following a discussion on soil temperatures at the plots and changes in such, the temperature and biodegradation rate relationship will be explored. Biodegradation rates using the van't Hoff-Arrhenius equation will be investigated and linear plots developed where possible. Additionally, biodegradation rates will be calculated and compared based on the equations used by the Eielson AFB project managers. Throughout this analysis effort, data within depth ranges will be kept separate and distinct from the others. It is important not to average data among the depths since contamination will be inconsistently distributed vertically and likely to migrate to the lower depths. However, it was assumed that the contamination is distributed homogeneously in the horizontal direction. Furthermore, it is important to examine the effectiveness of soil warming and changes in biodegradation over time. Averaging temperature or soil gas data covering

different seasons may not accurately depict what is truly occurring, e.g., the effect on

biodegradation rates in spring by adding warm water to soil already saturated with

melting snow.

IV. Results and Discussion

4.1 Plot Temperatures

Air injection and temperature monitoring began in August 1991. The full effect of soil warming from summer temperatures did not occur during this first year of operation (Leeson et al., 290-291). As shown by the data in Appendix A and Figures 8-11, the warm water method maintained higher temperatures than the others during the periods that warm water was being circulated. Before the heating was turned off, the average temperature in the warm water plot in the winter was above 10 °C. During the summer, temperatures usually ranged from 15 to 20 °C and reached 25 °C at one point. While the warm water was circulating, temperatures were usually highest at the 2.0 ft depth. During the winter months following the heating shutoff, this was not the case, as can be seen by Figure 8. The figures on the following pages show temperatures by depth, averaged from those thermocouples discussed at the end of Chapter III.

Illustrated by Figures 9 and 10, soil temperatures at the passive warming plot were 1 to 2 °C higher than the control plot with the latter staying below freezing until June. Adding plastic mulching to the passive warming plot increased this temperature difference to 7 and 8 °C. The heat tape method increased soil temperature to a maximum of 18.1 °C with winter temperatures kept at approximately 13 °C (Battelle, 96). The heat tape plot showed more consistent temperatures throughout the study; however, the data set has several gaps. The heat tape plot was located in a low-lying area where water accumulated following snow melt in late spring.

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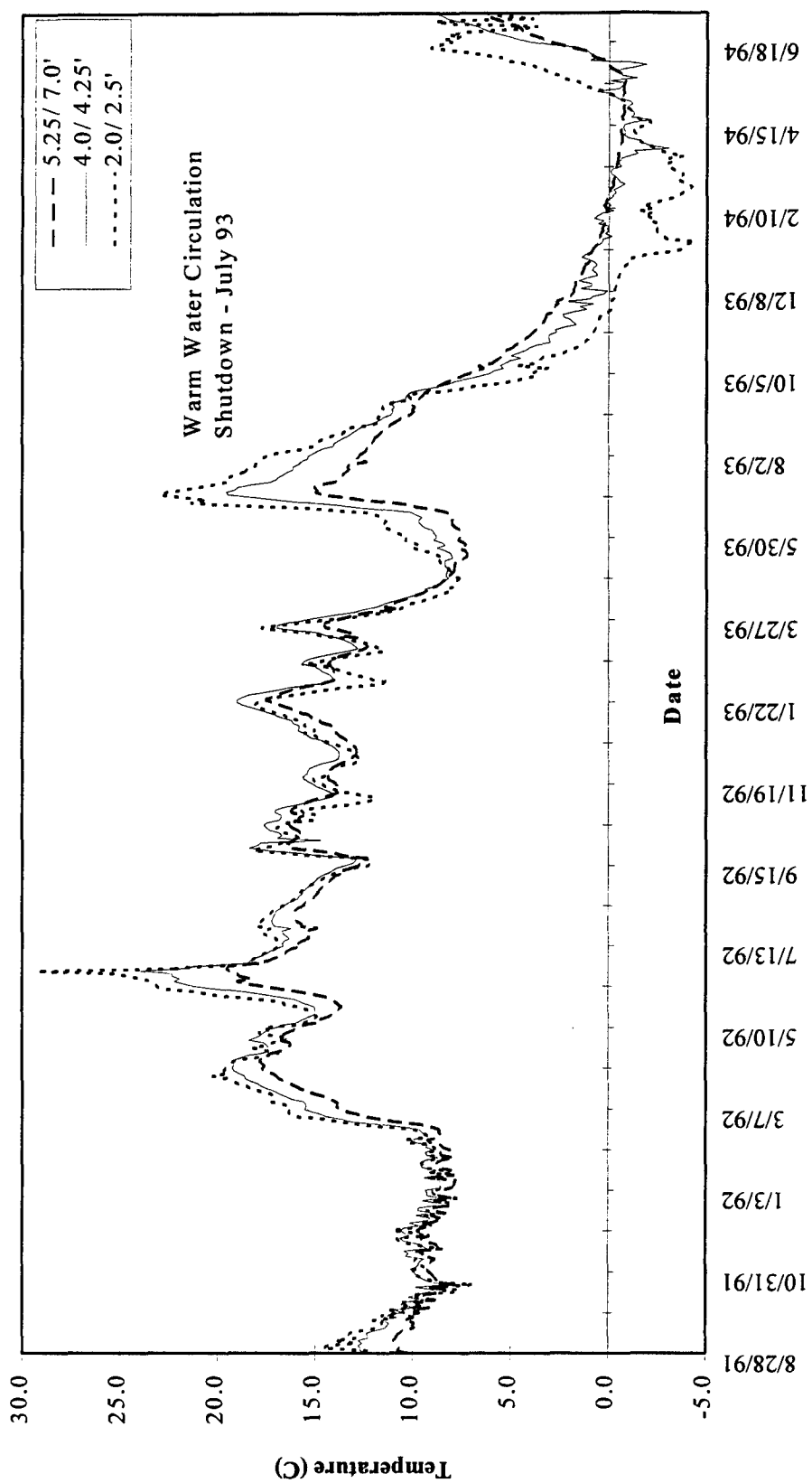
Figure 8: Soil Temperature by Depth - Warm Water Plot

72
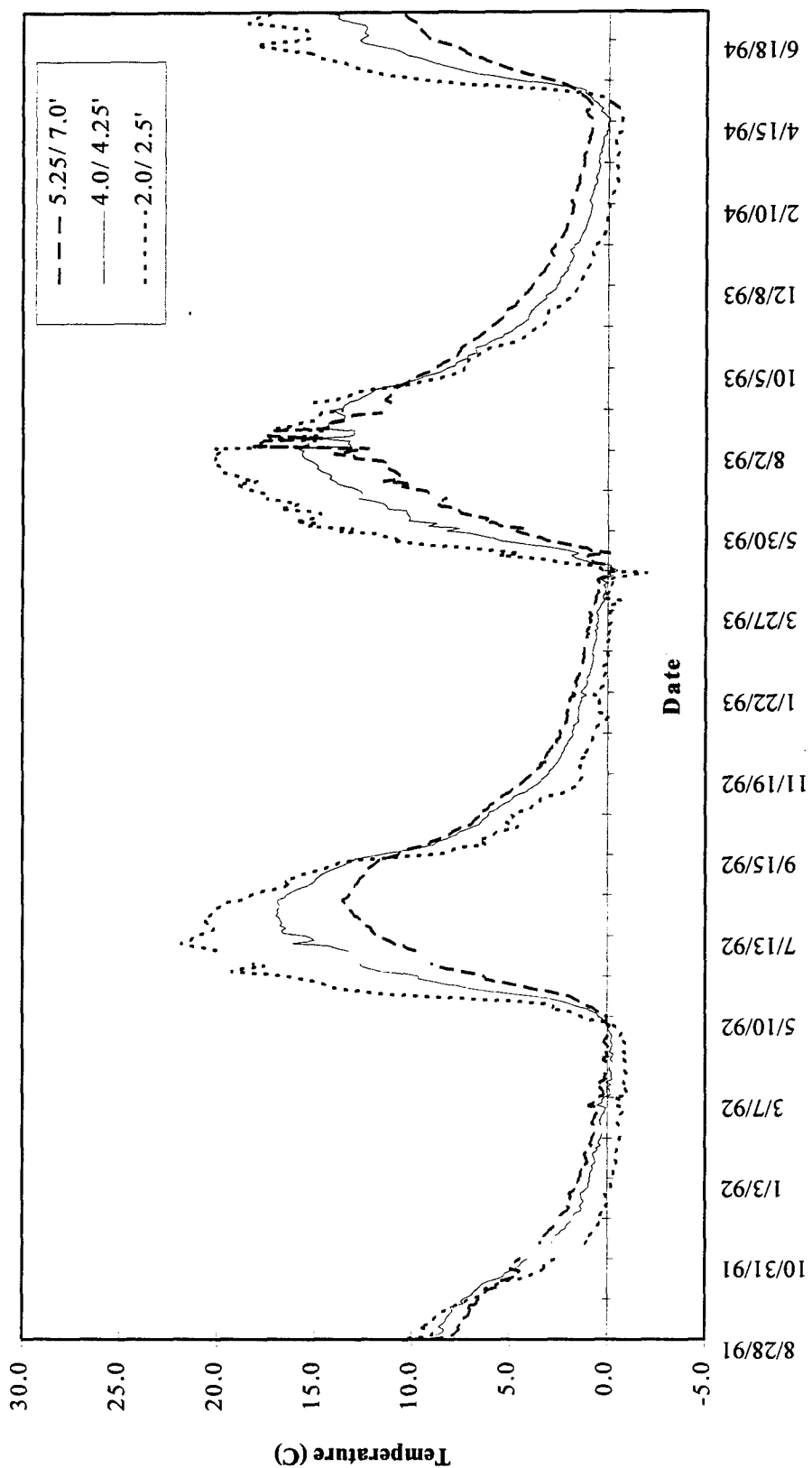
Figure 9: Soil Temperature by Depth - Passive Warming Plot

73
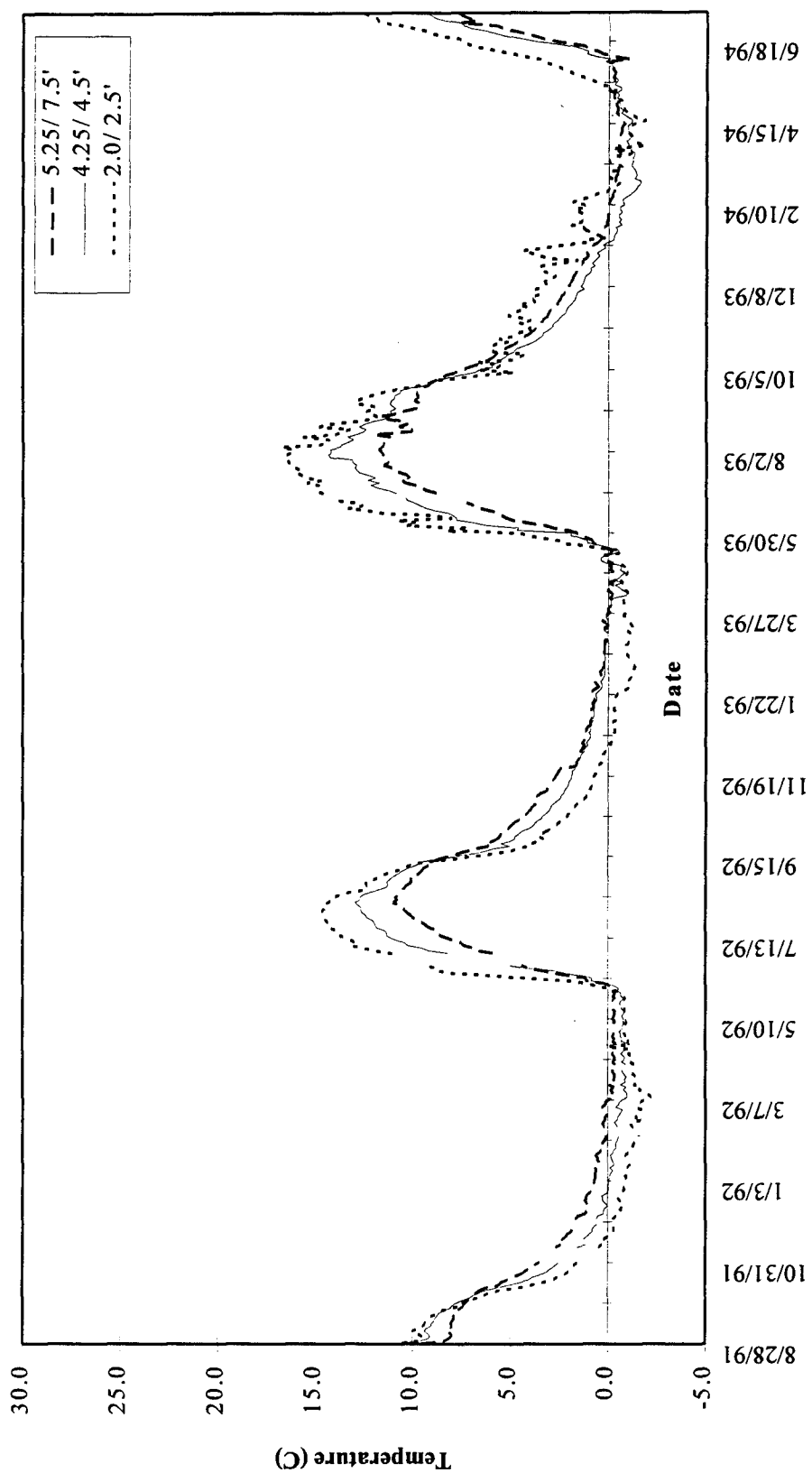
Figure 10: Soil Temperature by Depth - Control Plot
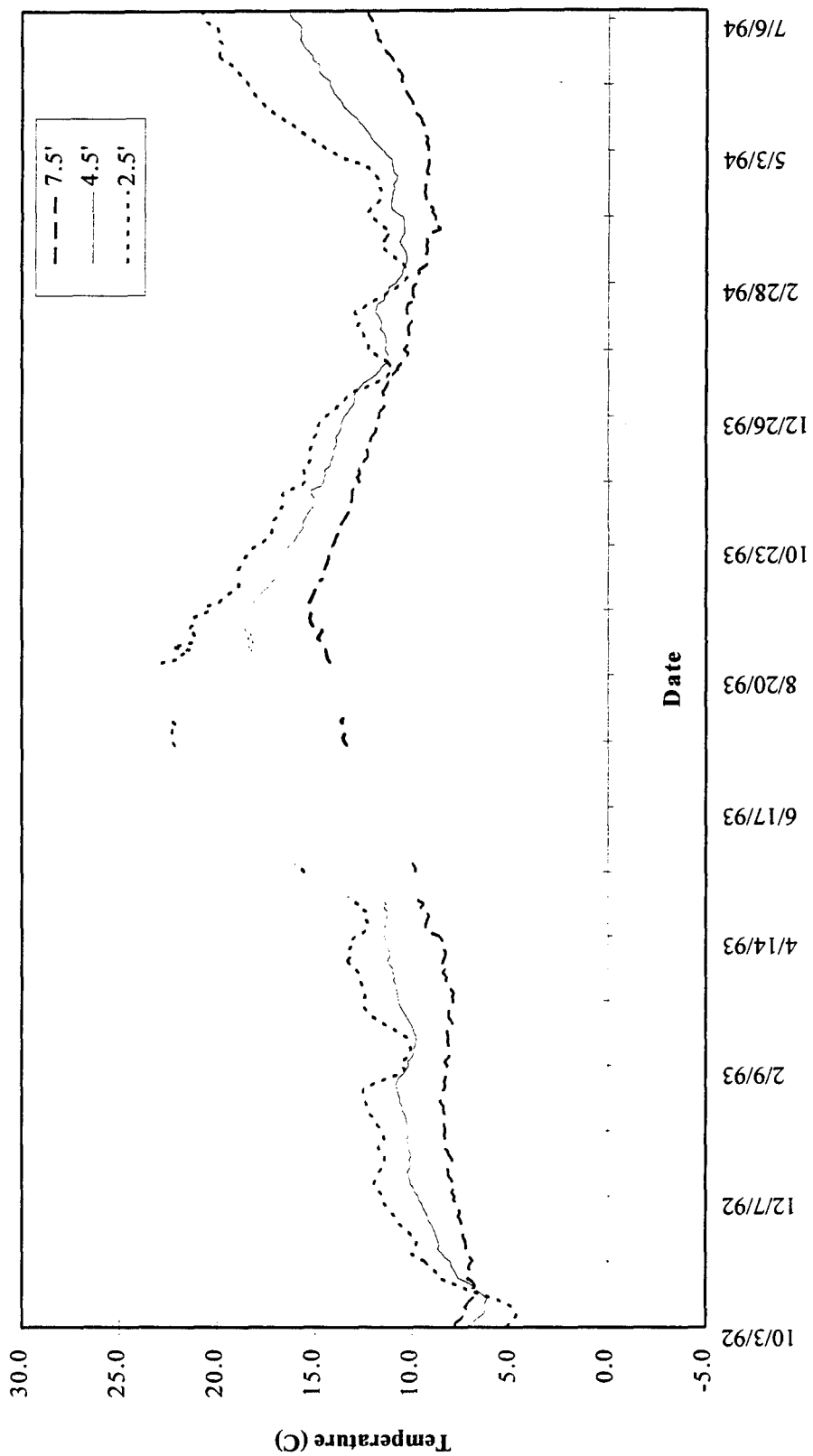
Figure 11: Soil Temperature by Depth - Heat Tape Plot

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As shown by Figures 8-11, the heat tape and warm water methodologies maintained higher soil temperatures. Dr. Leeson explained that they cycled the warm water circulation and heating in an attempt to balance plot temperature with soil moisture levels (Personal Communication). High levels of soil moisture could prevent oxygen diffusion through the soil and in the winter months the plot is more likely to freeze without high heat circulation. Therefore, groundwater flow velocity and direction are a major consideration when determining the placement of a remediation plot using warm water circulation. The water injected at the warm water plot could have adversely affected the heat tape plot by adding more water to that already present, especially in the winter and spring. Dr. Gregory Sayles stated that the heat tape plot was indeed downgradient from the warm water plot but, he believed that the water injected reached the groundwater table before reaching the heat tape plot (Personal Communication).

Given low energy costs, heat tape may be most effective technique to maintain a desired thermal gradient. Unlike the passive warming and control plots, temperatures at the shallow depth of 2.0 ft within the heat tape plot were consistently higher year-round. Since contamination migrates downward, the heat tape may be most effective in enhancing biodegradation if buried at a depth of 4 ft or deeper. At the control and passive warming plots, temperatures at shallow depths compared to higher depths were higher in the summer and lower in the winter; this annual shift confirms the temperature profile curve in Figure 2. When comparing the passive warming and control plots, the greatest

temperature difference among all depths occurred at the passive warming depth of 2.0 ft indicating that surface insulation and mulching greatly aid in heat retention.

The greatest difference among temperatures at the three depth ranges occurred within the heat tape plot. This temperature difference narrowed during the winter indicating a diminishing influence from the 3.0 ft buried heat tape. To summarize the preceding figures, Table 6 illustrates and compares the effectiveness of the different soil warming methodologies. The table shows seasonal soil temperatures averaged over all depths. Also shown are the maximum and minimum temperatures which typically occurred at the lowest or highest depths depending on the season.

Table 6: Summary of Soil Temperatures (°C) by Plot

Season	Warm Water Depth Avg.	Warm Water Max / Min	Passive Warm Depth Avg.	Passive Warm Max / Min	Control Depth Avg.	Control Max / Min	Heat Tape Depth Avg.	Heat Tape Max / Min
Summer 91	11.9	14.6 9.9	8.4	10.8 7.0	9.0	11.1 7.9		
Fall 91	9.6	12.0 6.9	3.6	8.0 -0.1	3.0	8.6 -0.9		
Winter 91	10.7	17.8 7.7	0.3	1.7 -1.1	-0.5	1.0 -2.3		
Spring 92	17.7	25.2 13.6	3.3	19.3 -1.0	0.1	9.4 -1.5		
Summer 92	16.2	29.2 12.2	14.8	21.9 7.6	10.7	14.7 4.7		
Fall 92	15.0	18.4 11.9	4.2	9.2 0.7	2.4	6.3 -0.4	8.3	12.0 4.7
Winter 92	15.0	19.0 11.4	0.9	2.5 -0.2	0.0	1.2 -1.4	10.1	12.6 7.9
Spring 93	9.8	16.9 7.2	4.0	16.8 -2.0	1.8	13.3 -1.1	11.3	16.3 8.2
Summer 93	14.1	22.9 8.6	14.4	20.3 8.3	12.3	16.7 7.3	18.0	22.9 12.5
Fall 93	3.2	9.3 -0.7	5.2	10.5 1.1	4.3	9.6 0.9	15.3	20.5 11.9
Winter 93	-0.8	1.4 -4.4	1.0	3.1 -0.5	0.2	4.4 -1.6	11.4	14.7 9.3
Spring 94	0.3	9.1 -3.8	4.4	18.1 -0.7	0.3	8.5 -1.9	12.4	19.9 8.6
Summer 94	6.2	8.9 3.6	13.4	18.5 9.5	8.4	12.6 4.4	16.0	20.8 11.5

4.2 Plot Respiration Rates

Determining accurate and representative respiration rates proved to be more difficult in the actively warmed plots -- warm water and heat tape; this is discussed later. Soil gas data taken during the in situ respiration tests was affected by numerous factors: adverse weather conditions, presence of high soil moisture, and interim data sampling error. Table 7 shows the number of linear regressions meeting the criterion of $R^2 \geq 0.45$.

The regressions were calculated from the tests taken which are presented in the draft project report.

Table 7: In Situ Respiration Test Data Regression Statistics

Plot	# Acceptable Regressions	Total # of Tests	Percent Acceptable
Warm Water	153	266	57.5%
Passive Warming	302	314	96.2%
Control	212	258	82.2%
Heat Tape	91	177	51.4%

Linear regressions with acceptable R^2 values were more consistently calculated from the soil gas data at the passive warming and control plots. Regressions from those plots typically had an R^2 value > 0.90. Data from the warm water and heat tape plots showed more scatter or had a poor linear fit. As a result of the data from those plots, a minimum R^2 value of 0.45 was established in order to get a sufficient number of oxygen consumption rates for comparison. In many instances, a positive slope was calculated or there were an insufficient number of data points to perform a linear regression. A sample sheet showing linear regression calculations is shown in Appendix B. As stated before, slopes calculated from the linear regression provide the oxygen consumption rate occurring at that point time and location. The complete slope data set is contained in Appendix C with the paired temperature data. This data set was used to compute averages and determine the effectiveness of the warming techniques on biodegradation.

4.3 Calculated Biodegradation Rates

In Chapter II, two equations are discussed which calculate a biodegradation rate, given field data. The third equation, van't Hoff-Arrhenius, is predictive and is discussed later in this chapter. Although the simplified rate equation published in the Bioventing Test Plan and Technical Protocol is derived from that published by Hinchee and Ong in 1992, a comparison of the results using both is performed. This is done since there is not a temperature factor included in the simplified equation. With the extreme cold temperatures and the changing environmental conditions, a comparison of the calculated biodegradation rates using both equations is useful and may help determine which equation, if either, is more valid.

4.3.1 Results Using Equation From Bioventing Test Plan and Technical Protocol

Using the equation below, biodegradation rates were calculated from the oxygen consumption data at the remediation site. With this equation, any inference into a biodegradation rate change with temperature is only demonstrated by matching rates with a time frame, i.e., date or month, or a temperature. Otherwise, comparing biodegradation as a function of temperature is ignored.

$$K_B [mg\ hexane/kg\ soil/day] = 0.8 \times K_{O2}\ [\%O_2/day] \qquad (13)$$

Biodegradation rates are a simple calculation using the measured oxygen consumption data. Oxygen consumption data was averaged within the three depth ranges which is included in Appendix D. Using the data in Appendix D, biodegradation rates in units of

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[mg-hexane/kg soil/day] are calculated and compared. The calculated rates are presented in Appendix E.

4.3.2 Results Using Equation Published in Hinchee and Ong (1992)

The biodegradation rate equation developed by Hinchee and Ong was discussed in Chapter II. Presented below, this relationship includes a temperature factor.

$$K \ [mg \ hexane/kg \ soil/day] = 5516 \times \frac{K_{O2}[\%O_2/hr]}{T[^\circ K]} \qquad (9)$$

Using the data in Appendix D, biodegradation rates in units of [mg-hexane/kg soil/day] are calculated and compared using both equations (9) and (13). The results are included in Appendix E.

4.3.3 Comparison of Calculated Biodegradation Rates

The biodegradation rates computed from the simplified equation compare well to those calculated with the Hinchee and Ong equation. The difference between computed rates is never greater than 6%. For the heat tape, passive warming, and control plots, using the simplified equation results in biodegradation rate estimates lower than those calculated by using the Hinchee and Ong equation. Within the relatively narrow temperature range observed in the data set, approximately 25 °C, the simplified equation proves to be an acceptable estimation for biodegradation. To model the biodegradation rates occurring at the plots, the two estimates were averaged together with the results plotted in Figures 12-15. As shown in the figures, several data points are missing which

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are indicated by broken lines. For example, Figure 12 shows that biodegradation rates

from in situ respiration test #2 were not available.
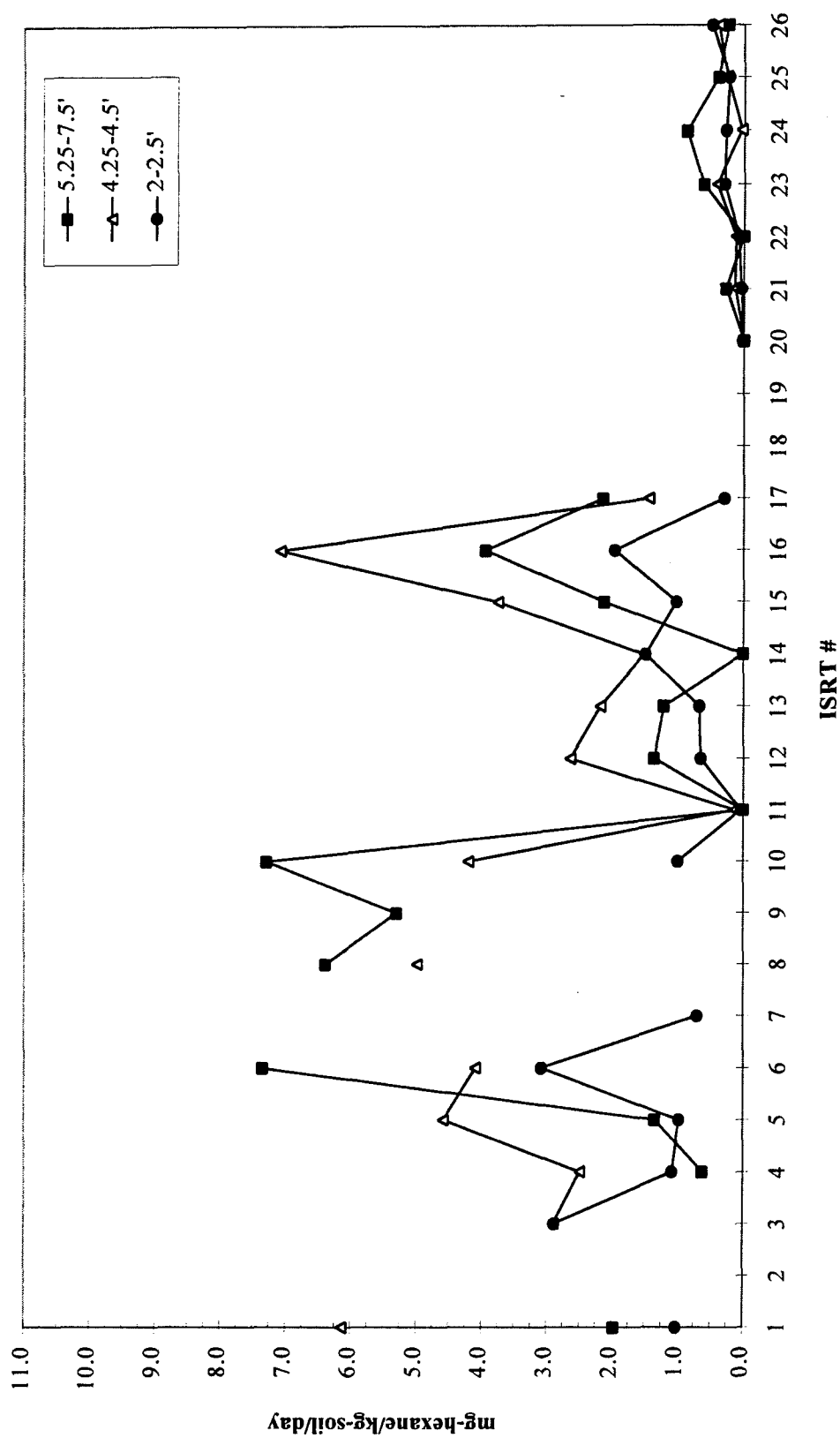
Figure 12: Biodegradation Rates - Warm Water Plot
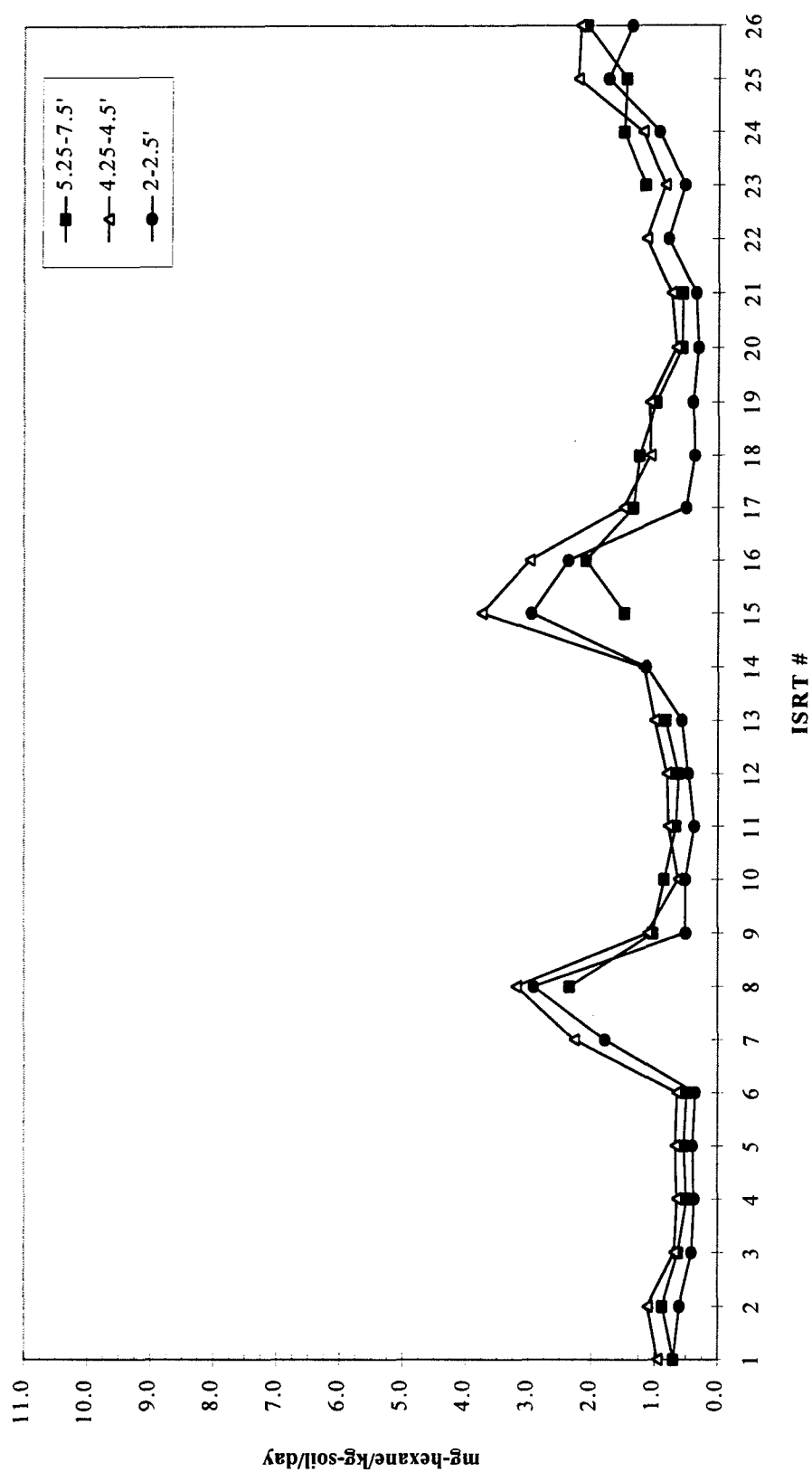
Figure 13: Biodegradation Rates - Passive Warming Plot
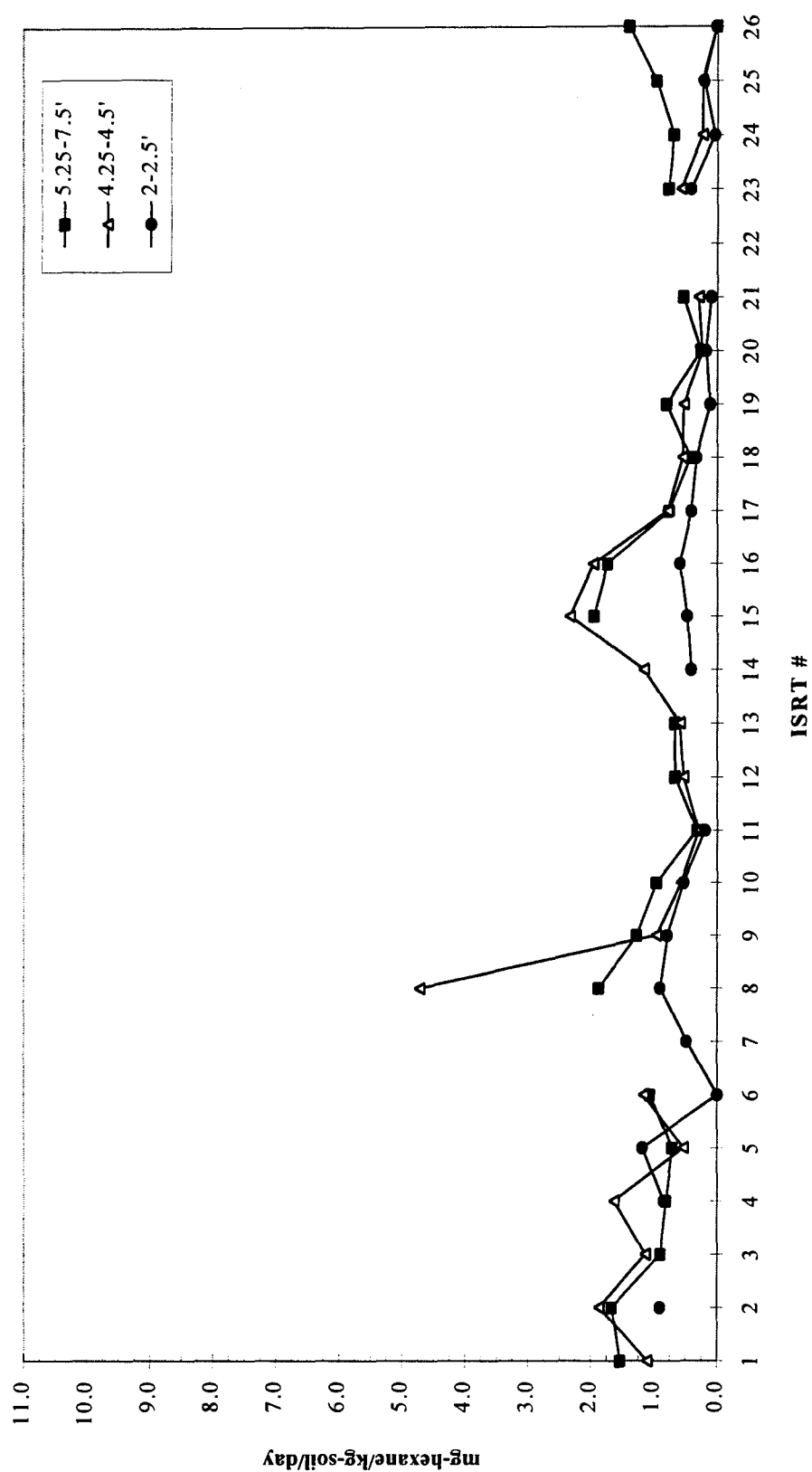
Figure 14: Biodegradation Rates - Control Plot
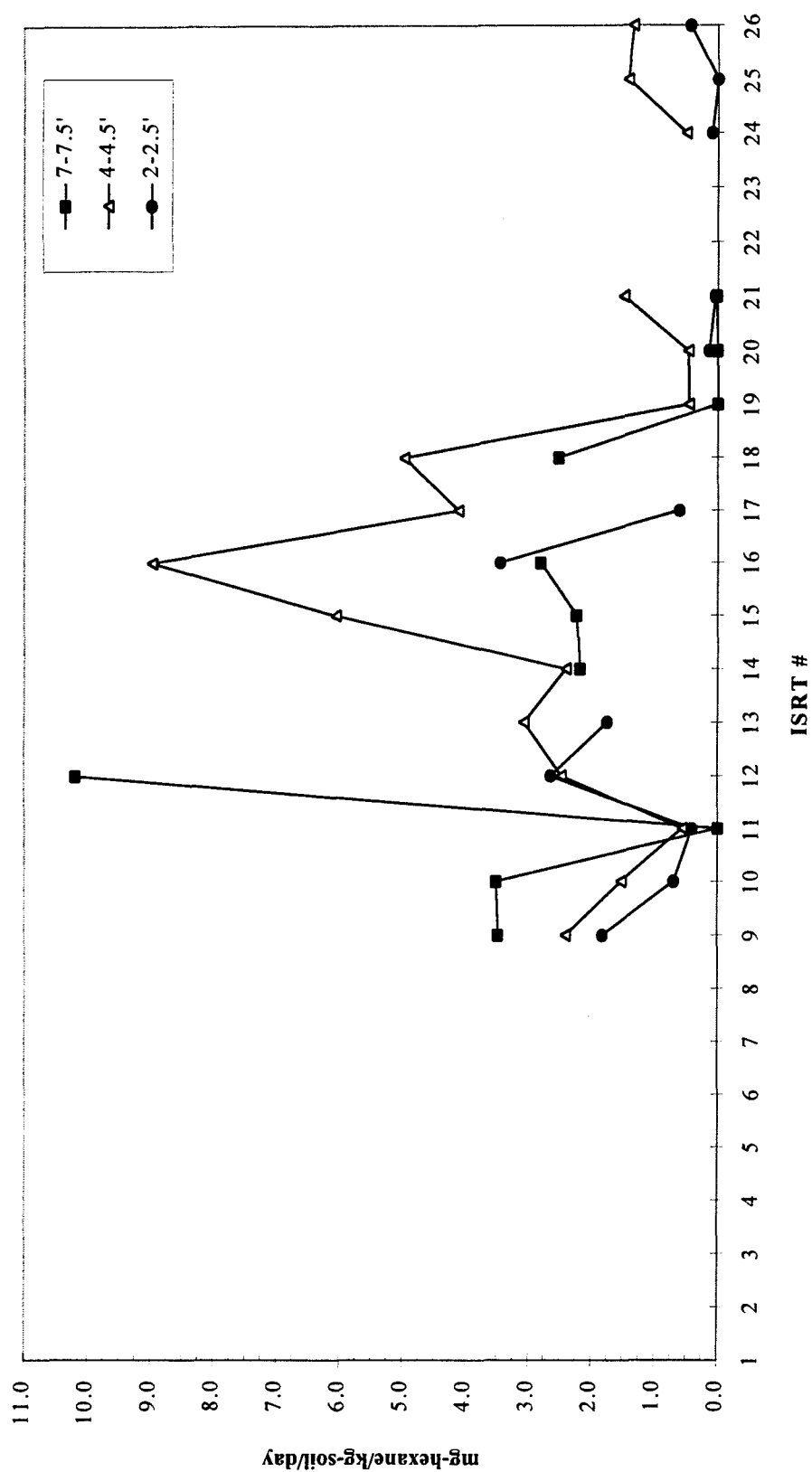
Figure 15: Biodegradation Rates - Heat Tape Plot

As shown by the previous figures and the data in Appendix D, the results were mixed. Rates at the warm water and heat tape plots were approximately double as the rates at the passive warming and control plots. A listing of the in situ respiration test dates is included in Appendix F.

At the warm water plot, the effect of turning off the warm water circulation is clearly visible. The water heating and circulation ceased a few days before ISRT #16 (24-28 Jul 93) when a subsequent decrease is noted. The last several tests illustrate a near zero biodegradation rate indicating either the contamination was cleaned up or little microbial activity was present. Rates at the shallow depth of 2 - 2.5 feet were typically less than that at the lower depths. Furthermore, Dr. Sayles stated that the contamination concentration was lower in the warm water plot (Personal Communication). Therefore, one would expect lower respiration rates when compared to a more contaminated plot. Here, this was not the case. It is obvious that higher soil temperatures in the warm water plot resulted in higher microbial respiration rates despite the possibility of lower contamination concentration. This soil warming technique demonstrated good results.

At the passive warming plot, biodegradation rates are more consistent with the seasonal trend in soil temperatures. Biodegradation rates, like soil temperatures, at the shallow depths are typically lower in the winter and higher in the summer. Since biodegradation depends on the level of contamination which is likely to migrate downward, it is not surprising that the highest rates do not occur at the depth of 2 - 2.5 feet.

Biodegradation rates at the control plot were mixed. Initially, they were greater than the passive warming rates. After ISRT #6 (18-23 April 92), rates at the control plot become less. This may indicate the lag time required at the passive warming plot for the insulation and coverings to become effective Additionally, the rates at the control plot did not follow the trend observed at the passive warming plot and were more inconsistent.

Finally, the heat tape plot showed the highest biodegradation rates. Although there were fewer data points and the results were more inconsistent, it appears that the heat tape had the greatest effect. In the winter and spring, rates decrease to near zero due to the plot's location in a low-lying area and the resulting water saturation from snow melt.

4.4 Predicting Biodegradation Using the van't Hoff-Arrhenius Relationship

The paired temperature-soil gas data was also modeled using the van't Hoff-Arrhenius relationship under three different scenarios each at three depth ranges: 5.25-7.5 ft, 4.25-4.5 ft, and 2-2.5 ft. To effectively use this relationship, it is important to have data covering a wide temperature range. Unfortunately, temperatures at the passive warming and control plots did not change significantly during the year. Additionally, data should cover the entire temperature range instead of only the two extremes, winter and summer. The data analysis scenarios examined were as follows:

1) Warm water, passive warming, and control plots during 10 Nov 1991 - 12 Nov 1992. This first year of data should show remediation of the most

contamination. The data from the first in situ respiration test was excluded to allow additional time for the plots to warm up from the individual techniques.

2) Data from all plots during the project lifespan, 1 Oct 1991 - 9 Jul 1994. At the end of any remediation project, respiration rates are expected to be lower despite high temperatures since most of the contamination is already cleaned up.

3) Data from all plots averaged by in situ respiration test and within depth ranges.

The following tables summarize the results using the van't Hoff-Arrhenius relationship and were derived from linear plots developed with $[1/^{\circ}K]$ as the X-coordinate and $[ln(\%O_2\ consumed/hr)]$ as the Y-coordinate (see Eq (4)).

Table 8: van't Hoff-Arrhenius Results - Data from 10 Nov 91 - 12 Nov 92

	Warm Water			Passive Warming			Control		
	5.25-7.5'	4.25-4.5'	2-2.5'	5.25-7.5'	4.25-4.5'	2-2.5'	5.25-7.5'	4.25-4.5'	2-2.5'
Intercept	105.72	28.15	10.53	30.55	26.30	25.66	23.67	30.30	-3.38
Slope [$^\circ$K]	-30990	-8586	-3795	-9350	-8125	-8080	-7325	-9091	56
R^2 value	0.768	0.489	0.079	0.818	0.745	0.820	0.263	0.601	0.000
Activation Energy [kcal/mol]	61.58	17.06	7.54	18.58	16.15	16.05	14.56	18.06	-0.11
Frequency Factor [%O_2/hr]	8.2E+45	1.7E+12	3.7E+4	1.9E+13	2.6E+11	1.4E+11	1.9E+10	1.4E+13	0.03

Table 9: van't Hoff-Arrhenius Results - Data from 1 Oct 91 - 9 Jul 94

	Warm Water			Passive Warming			Control			Heat Tape		
	5.25-7.5'	4.25-4.5'	2-2.5'	5.25-7.5'	4.25-4.5'	2-2.5'	5.25-7.5'	4.25-4.5'	2-2.5'	7-7.5'	4-4.5'	2-2.5'
Intercept	29.33	41.90	26.76	21.56	21.35	21.14	20.69	24.09	14.76	-14.09	32.07	-2.89
Slope [$^\circ$K]	-9002	-12657	-8661	-6818	-6724	-6815	-6559	-7549	-5281	3392	-9830	-281
R^2 value	0.381	0.487	0.294	0.524	0.600	0.669	0.317	0.255	0.112	0.008	0.140	0.000
Activation Energy [kcal/mol]	17.89	25.15	17.21	13.55	13.36	13.54	13.03	15.00	10.49	-6.74	19.53	0.56
Frequency Factor [%O_2/hr]	5.5E+12	1.6E+18	4.2E+11	2.3E+9	1.9E+9	1.5E+9	9.6E+8	2.9E+10	2.6E+6	0.000	8.4E+13	0.06

Table 10: van't Hoff-Arrhenius Results - Data Averaged from Respiration Tests

	Warm Water			Passive Warming			Control			Heat Tape		
	5.25-7.5'	4.25-4.5'	2-2.5'	5.25-7.5'	4.25-4.5'	2-2.5'	5.25-7.5'	4.25-4.5'	2-2.5'	7-7.5'	4-4.5'	2-2.5'
Intercept	34.10	41.16	19.70	23.06	23.18	21.50	23.61	11.87	-4.18	-32.61	44.66	11.58
Slope [°K]	-10361	-12444	-6606	-7235	-7215	-6902	-7374	-4213	11.1	8755	-13457	-4359
R^2 value	0.609	0.555	0.290	0.650	0.840	0.831	0.450	0.056	0.000	0.319	0.231	0.022
Activation Energy [kcal/mol]	20.59	24.73	13.13	14.38	14.34	13.71	14.65	8.37	-0.02	-17.40	26.74	8.66
Frequency Factor [%O₂/hr]	6.4E+14	7.5E+17	3.6E+8	1.0E+10	1.2E+10	2.2E+9	1.8E+10	1.4E+5	0.015	6.9E-15	2.5E+19	1.1E+5

As can seen by the previous tables, based on the R^2 values the van't Hoff-Arrhenius relationship is an acceptable predictor of the biodegradation rate based on temperature in some instances. At the passive warming plot, the relationship in all scenarios can be assumed to accurately model what occurred; the R^2 values indicate that this relationship can be used to predict the biodegradation rate at any temperature. At the warm water plot, the relationship holds best at the two lowest depth ranges as shown by Table 10. Furthermore, the activation energies and frequency factors at the warm water plot are significantly higher than those at the passive warming plot. The higher moisture content at the warm water plot may have a detrimental effect on the microbial community which may require additional energy to overcome the water injected. Additionally, activation energy is lowest at the shallow depth for both the passive warming and warm water plots.

For the control and heat tape plot, the van't Hoff-Arrhenius relationship was a poor predictor as indicated by their lower R^2 values. Ignoring the R^2 values, the tables show that there were both a positive and negative slope values at the heat tape and control plots in two scenarios each; a positive slope is another indicator that the van't Hoff-Arrhenius relationship can not be applied. The relationship models the increase in biodegradation with increased temperature which is contradicted by a positive slope. At the 2-2.5 ft depth for the control plot and the 7-7.5 ft depth for the heat tape plot, activation energies are negative values indicating the mineralization of the JP-4 contaminant is spontaneous and requires no initiation. Conceptually, this contradicts the van't Hoff-Arrhenius model applied in this study. In view of these results, it is visible

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that any Arrhenius model of the heat tape and control plots would be questionable or inaccurate.

Additionally, preserving the data within depth ranges, distinct and separate, is important as illustrated by the tables. Based on R^2 values, the lower depths were better modeled by the van't Hoff-Arrhenius equation which may indicate increased respiration rates arising from the presence of sufficient contamination for microbial activity. These results validate an earlier statement that the contamination concentration is higher at the lower depths migrating downward. As discussed in Chapter II, this equation relies on the assumptions that contaminant concentration and amount of active biomass are constant over time. Using data averaged over all depths would ignore the expectation that petroleum products migrate down through the soil and are distributed inconsistently in the vertical direction.

Described as scenario #3 with data presented in Table 10, the following van't Hoff-Arrhenius charts were developed using data averaged during the in situ respiration tests for only the warm water and passive warming plots. For the remainder of the data analysis, this scenario will be used and modeled since it appears to best illustrate the biodegradation and temperature relationship at the two plots.
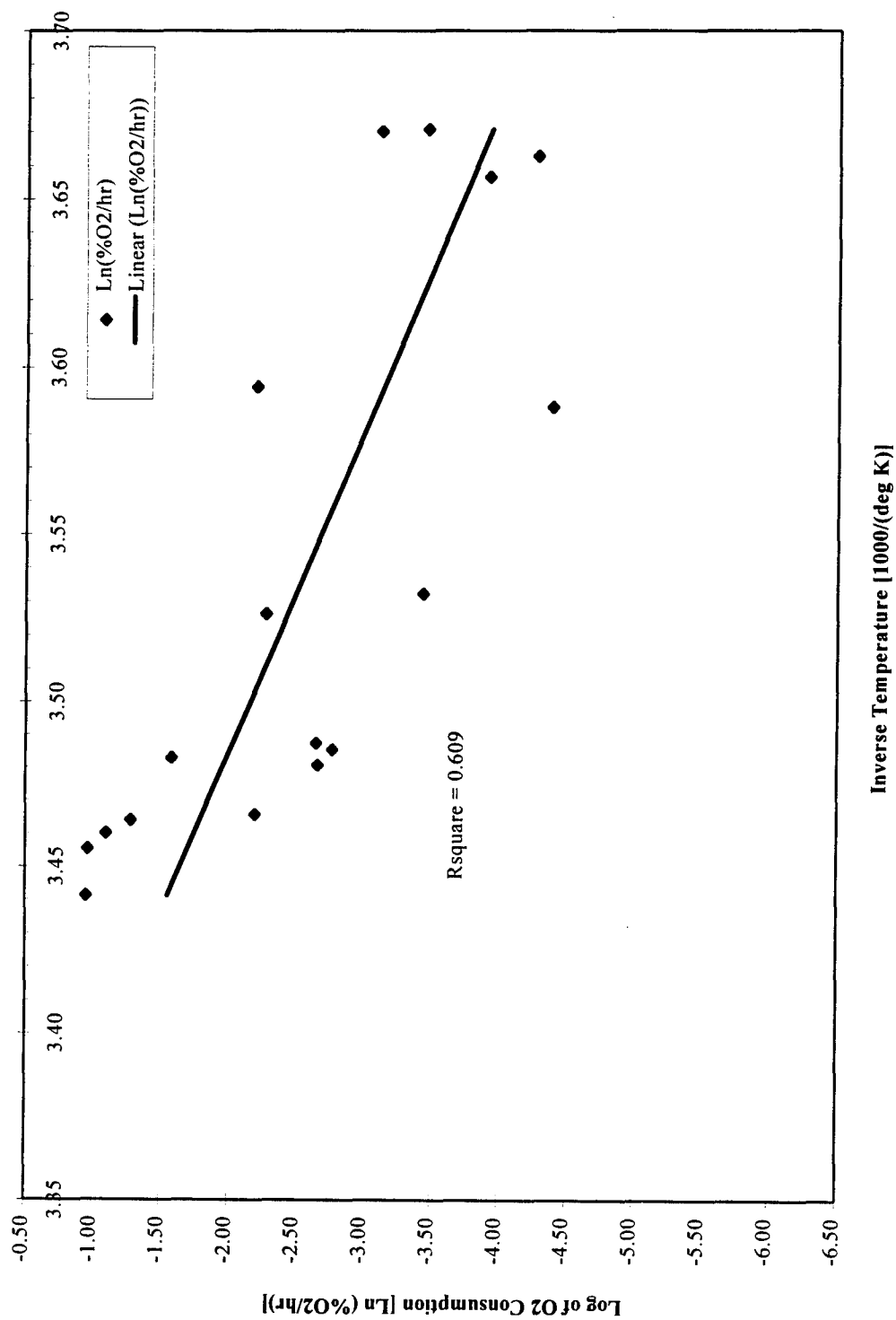
Figure 16: Arrhenius Relationship - Warm Water Plot (5.25 - 7.5 ft)
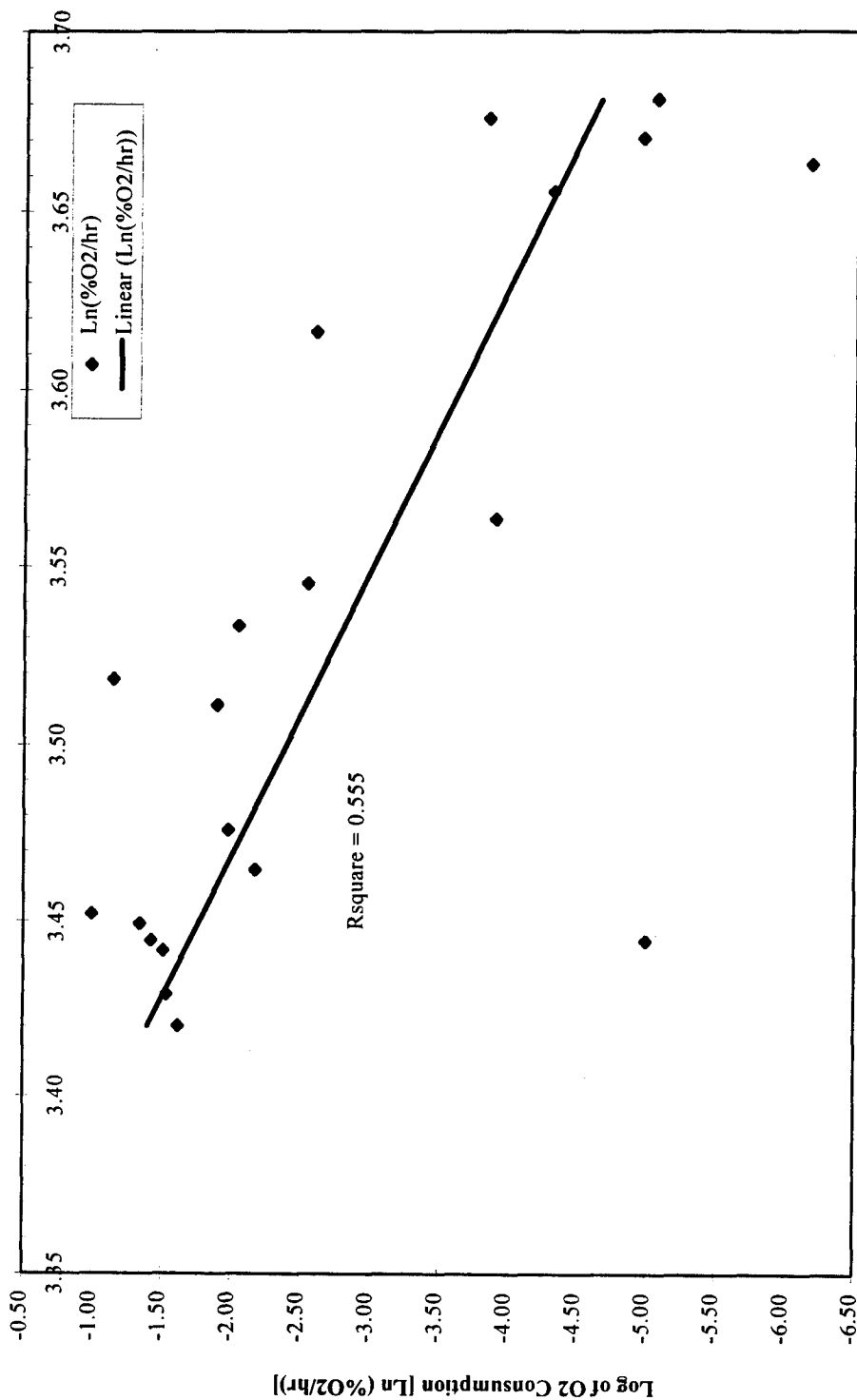
Figure 17: Arrhenius Relationship - Warm Water Plot (4.25 - 4.5 ft)

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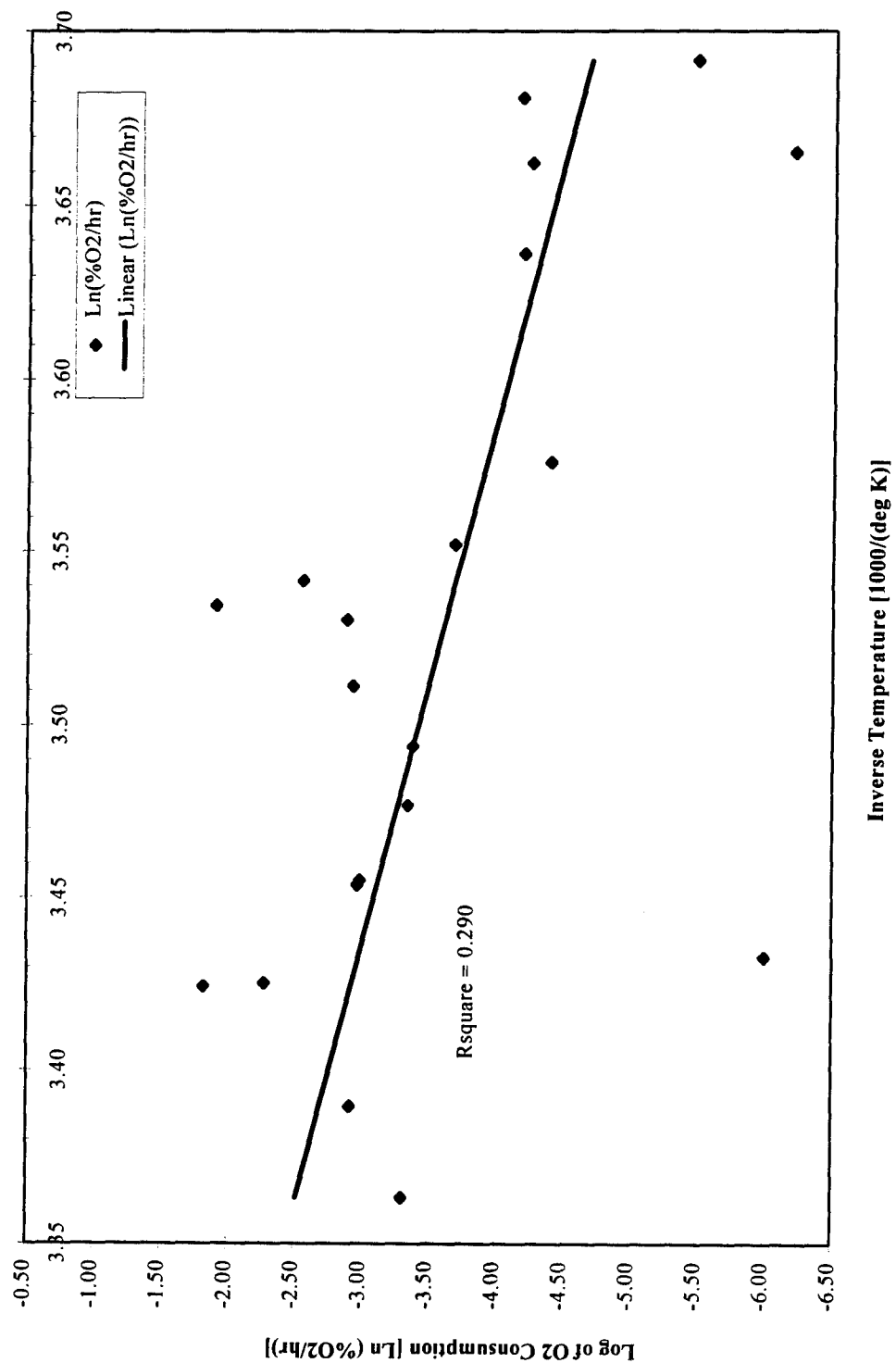
Figure 18: Arrhenius Relationship - Warm Water Plot (2 - 2.5 ft)
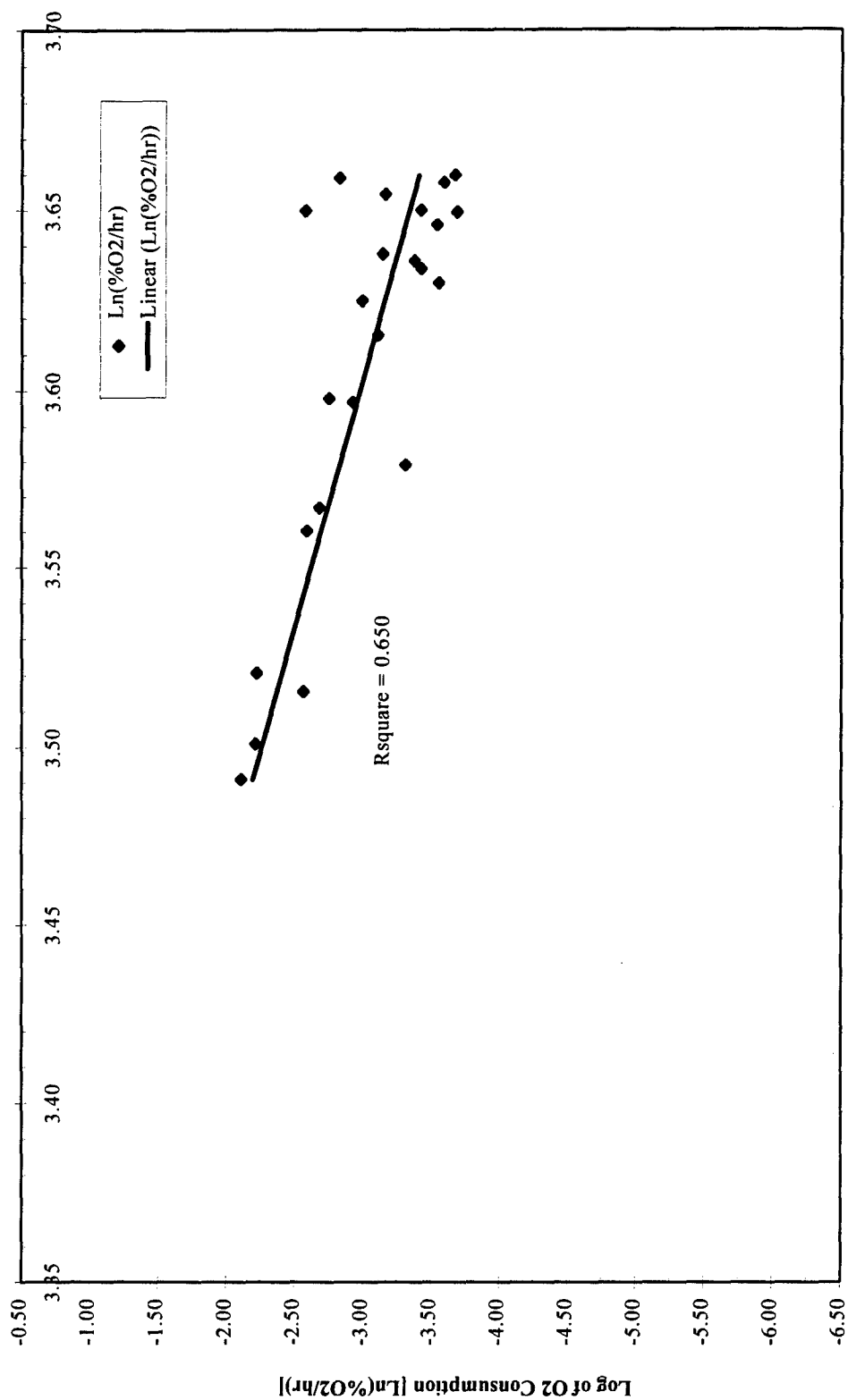
Figure 19: Arrhenius Relationship - Passive Warming Plot (5.25 - 7.5 ft)
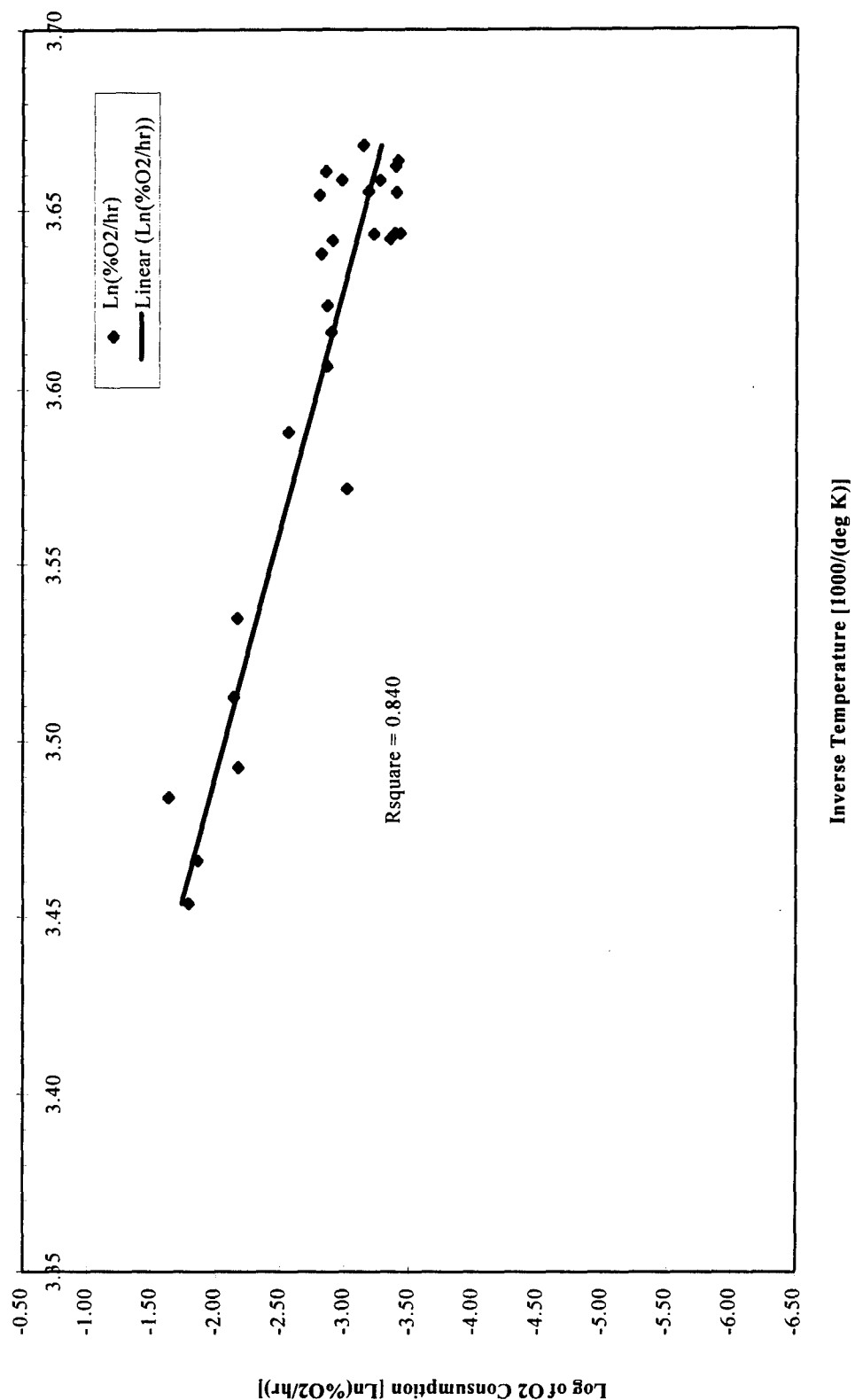
Figure 20: Arrhenius Relationship - Passive Warming Plot (4.25 - 4.5 ft)

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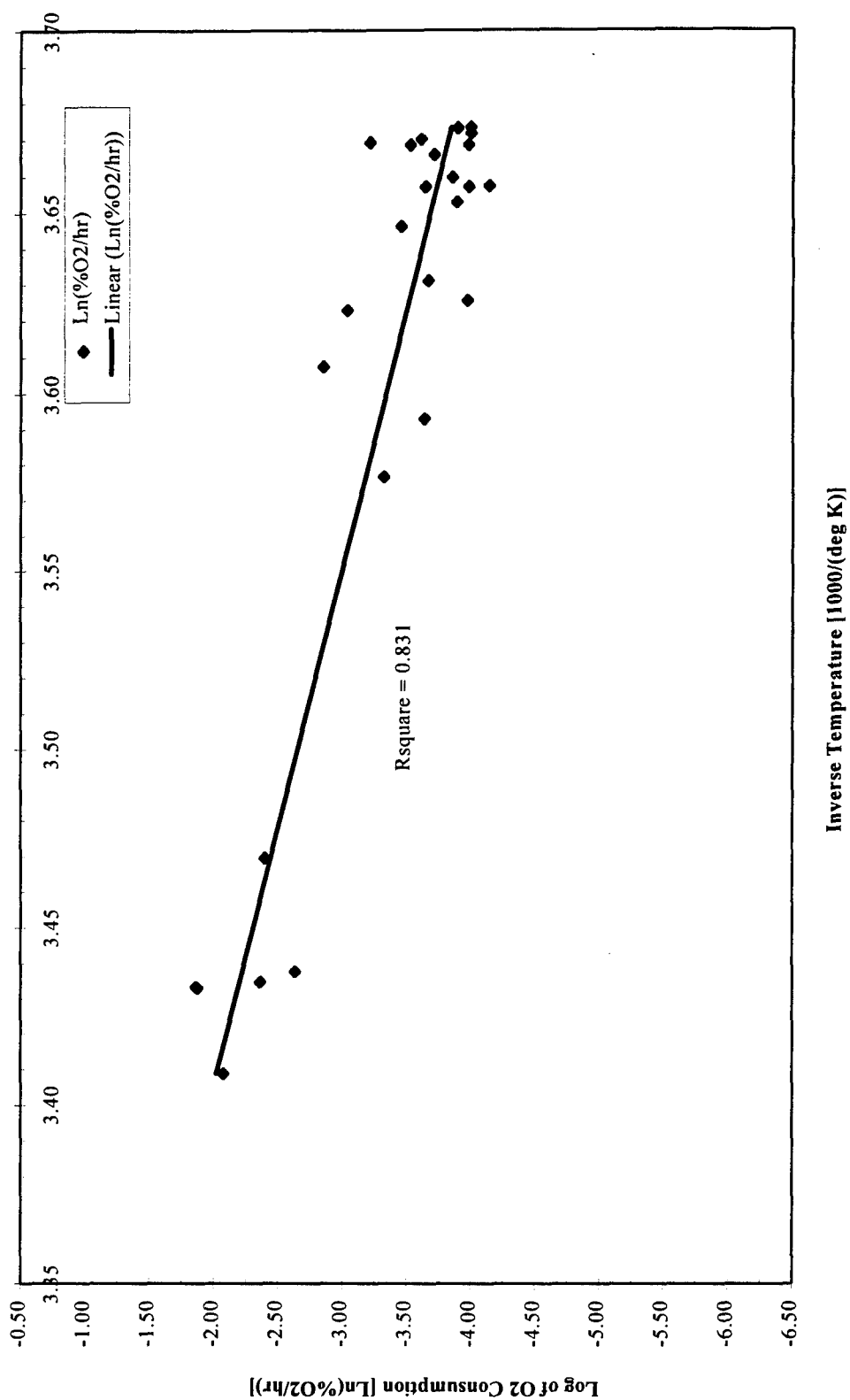
Figure 21: Arrhenius Relationship - Passive Warming Plot (2 - 2.5 ft)

As seen by the previous figures, biodegradation increased with temperature. Despite more data scatter, the warm water charts show a steeper slope than the passive warming charts which is also indicated in Tables 8-10. The steeper slopes result from higher respiration rates occurring over the same temperature range and validate the contention of higher biodegradation rates at the warm water plot. Temperature data from the warm water plot covered a wider range which is preferred when modeling the van't Hoff-Arrhenius relationship.

To further validate the results of the Arrhenius charts, comparisons were made against the few models published using this relationship. In his Ph.D. dissertation, Ross Miller published Arrhenius plots from his bioventing study at Tyndall AFB, Florida. Additionally, Dr. Gregory Sayles published Arrhenius plots in two instances, 1993 and 1995. The next few figures compare an average Arrhenius line calculated from the data used in this thesis effort against that published by Miller and Sayles. For the warm water plot, the shallow depth data was excluded in calculations and is not graphed due to its low R^2 value.
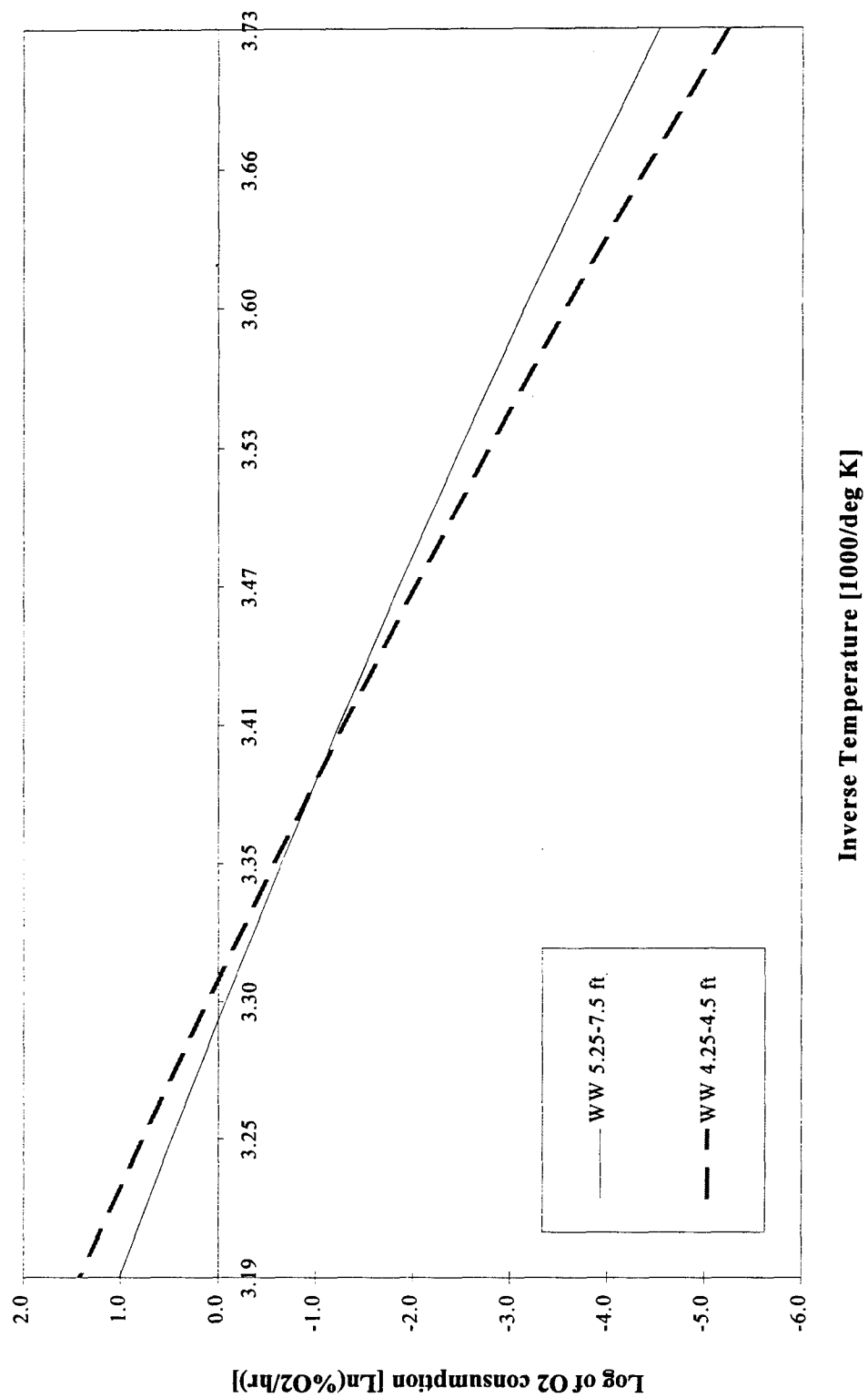
Figure 22: Arrhenius Relationship - Warm Water Plot by Depth

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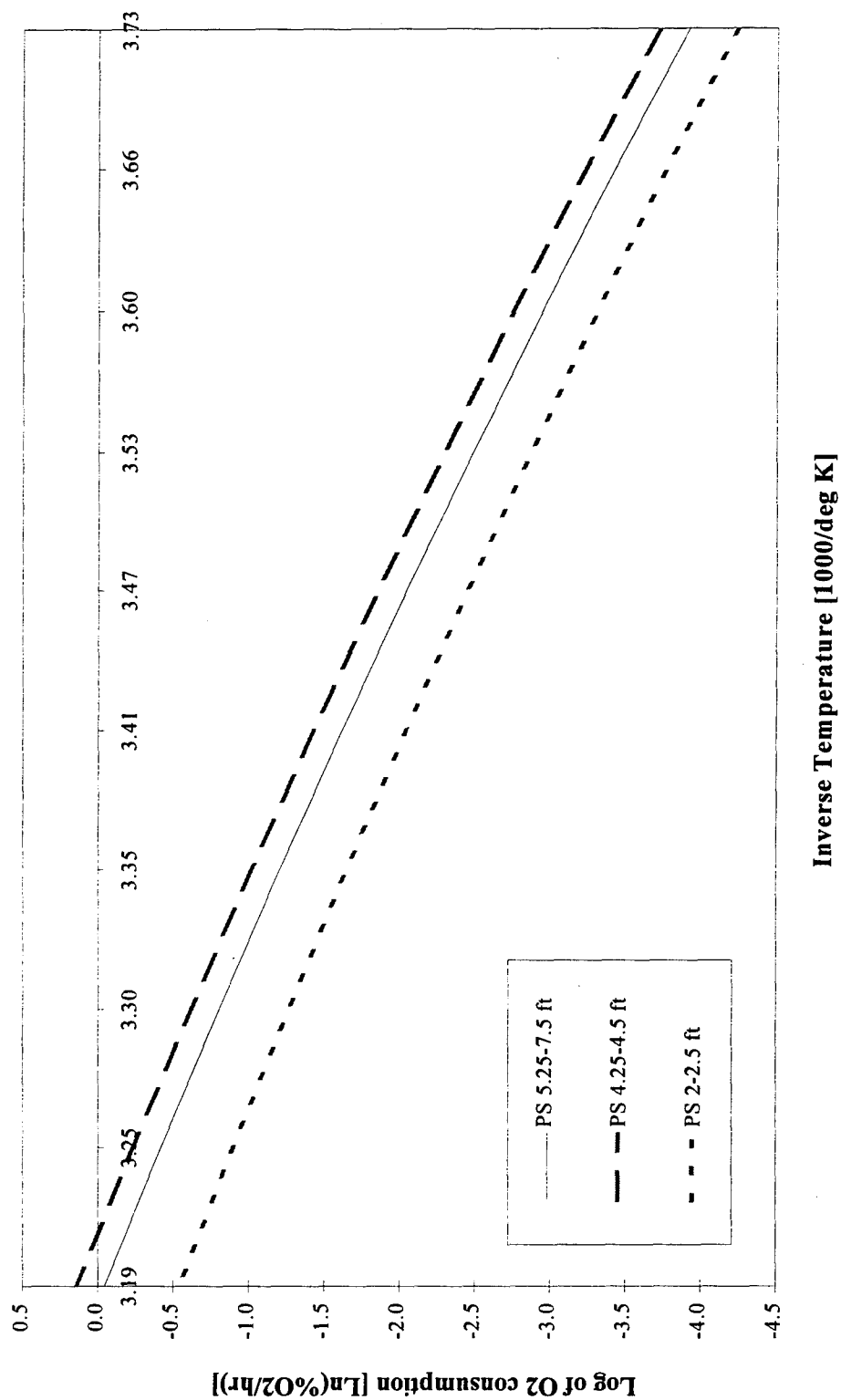
Figure 23: Arrhenius Relationship - Passive Warming Plot by Depth
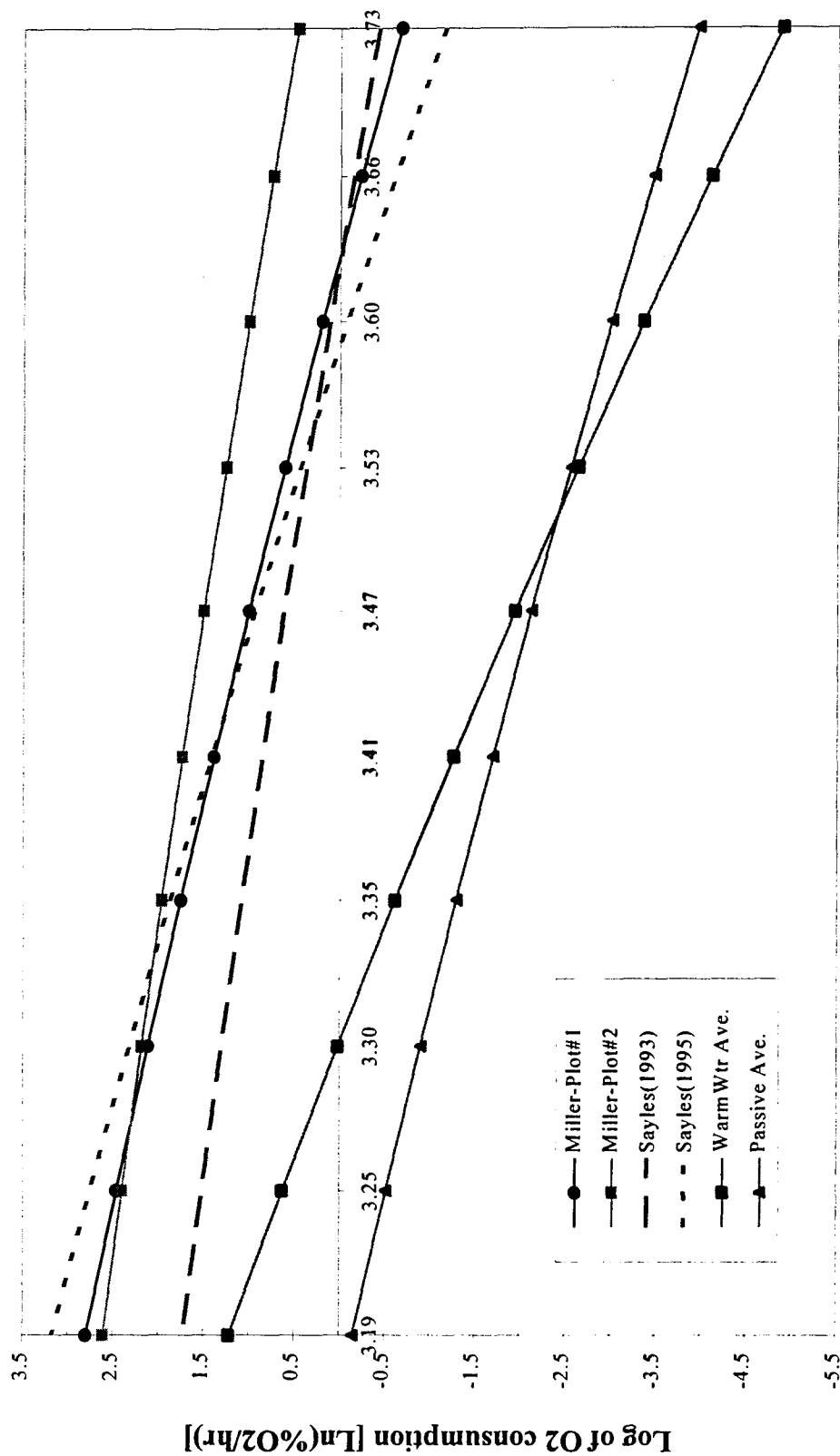
Figure 24: Arrhenius Relationship - Comparison with Miller and Sayles

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The Arrhenius line charts show higher biodegradation rates occurring at the warm water plot which is illustrated by a higher intercept, see also Table 10. The warm water Arrhenius lines also have a steeper slope indicating a higher activation energy. The lines calculated and plotted in Figures 22 and 23 were averaged individually and compared in Figure 24 to Arrhenius plots published by Miller and Sayles.

The results achieved by Miller and Sayles are consistent with each other; however, there is disparity between their results and the data developed in this study. This difference could arise from several factors. The bioventing study by Miller was performed in Florida at a site with soil having a higher sand content. Both oxygen and moisture will diffuse more easily at a site with a sandy soil. Injected oxygen will reach deeper into the site and be distributed more consistently through a site with a higher porosity. Water will also move through the soil reaching the groundwater table and transfer heat quicker. Furthermore, soil temperatures in Florida are higher.

The chemical kinetics and microbial population within soils at Alaska and Florida may be very different. In the Florida climate, microorganisms do not face freezing soil temperatures. They are not required to acclimate to varying seasonal temperatures as those microbes in Alaska do. The Alaskan microorganisms must acclimate to summer temperatures every year; this annual activity alters both the frequency factor and activation energy observed at Alaska. Furthermore, the chemical kinetics at Alaska and Florida may be more complex than can be modeled by using the van't Hoff-Arrhenius relationship. While this may explain the dissimilarity between this study's Arrhenius

plots compared to Miller, it does not address the differences with those plots developed by Sayles.

The soil gas data used in this study was screened based on a minimal acceptable R^2 value. As shown in Table 7, almost half of the soil gas data from the in situ respiration tests at the warm water and heat tape plots were discarded due to poor line fit and high data scatter. Furthermore, soil temperatures were paired with individual oxygen consumption rates at a specific depth range, probe location, and point in time. In this study, only the two lowest depths of the warm warming plot and all depths at the passive warming plot could be modeled by the van't Hoff-Arrhenius relationship based again on a minimally acceptable R^2 value.

On the hand, the data set used by Sayles included the entire site's soil gas measurements which exhibited a negative slope. His Arrhenius models used a soil temperature averaged over all depths for each plot. These average plot temperatures were matched with the oxygen consumption rates. His data set included soil gas and temperature measurements from all four test plots. The higher rates observed in the Sayles' Arrhenius lines may arise from the inclusion of the heat tape plot data which had higher biodegradation rates and higher soil temperatures. As shown by this study in Table 10, at the depth of 7.0-7.5 ft the Arrhenius line had a positive slope and a negative activation energy in the two scenarios modeled which contradicts the implication of the van't Hoff-Arrhenius relationship. Additionally, the middle depth, 4.0-4.5 ft, has the

highest frequency factor. Including this data would shift the Arrhenius lines from this study upward.

4.5 Remediation Effectiveness at Eielson AFB

Follow-up soil gas sampling was conducted in March, May, and July 1994. Table 11 shows the final soil gas sampling performed at the conclusion of the project (Battelle, Appendix K6-K8).

Table 11: Distribution of Contaminants in Soil Gas Samples in July 1994

Compound	Concentration (ppmv) at Location					
	P2B	P5B	P6B	B2B	C4B	H1B
Total C_5 -C_{15}	3.31	0.613	0.696	<0.005	0.808	1203
Total C_6	3.59	0.668	0.724	0.293	0.863	1270
Benzene	<0.005	<0.005	<0.005	<0.005	<0.005	13.12
2,4-Dimethylpentane	<0.007	<0.007	<0.007	<0.007	0.012	516
Ethylbenzene	<0.004	<0.004	0.079	<0.004	<0.004	0.746
n-Heptane	<0.005	0.055	<0.005	<0.005	<0.005	25.1
n-Hexane	<0.005	<0.005	<0.005	<0.005	<0.005	13.3
2-Methylpentane	<0.007	<0.007	<0.007	<0.007	<0.007	100
n-Octane	<0.004	<0.004	0.071	<0.004	<0.004	<0.004
Toluenes	<0.003	0.052	<0.004	<0.004	<0.004	<0.004
p-Xylenes	<0.003	<0.003	<0.003	<0.003	<0.003	0.059

Description of Locations:
P2B, P5B, and P6B   Passive warming plot probes all at a depth of 4.25 ft
B2B   Background probe at a depth of 4.25 ft
C4B   Control plot probe at a depth of 4.25 ft
H1B   Heat Tape plot probe at a depth of 4.5 ft

Table 11 shows a significant decrease in levels of TPH and BTEX compounds as compared to the initial soil gas samples taken which are reflected in Table 4. Figures 25 and 26 below illustrate the magnitude of this decrease in contaminant levels and the effectiveness of this remediation effort (Battelle, 114-115).
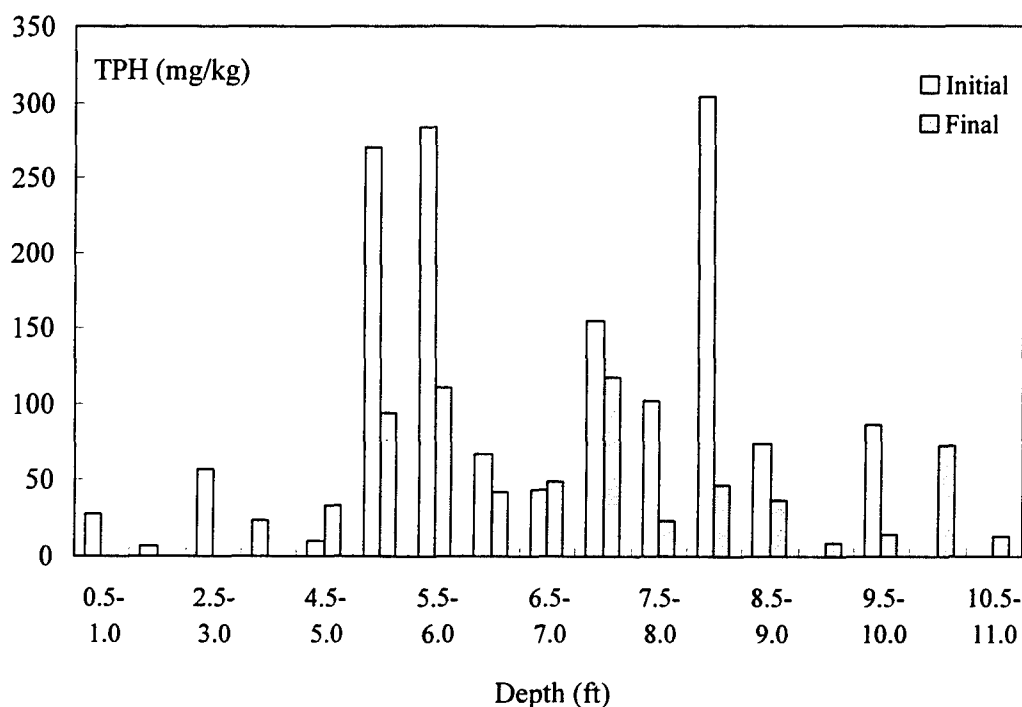
Figure 25: Initial and Final Average TPH Soil Concentrations by Depth

This figure indicates a significant decrease in TPH levels at the shallow and middle depths of the contaminated site. Residual hydrocarbon contamination remains at the lower depths where compounds with a higher density and less biodegradability are present. Additionally, the soil temperature and microbial populations at these depths are much lower in part due to the groundwater temperature. The soil warming techniques

coupled with bioventing were very successful in remediating the BTEX compounds as

indicated in Figure 26.
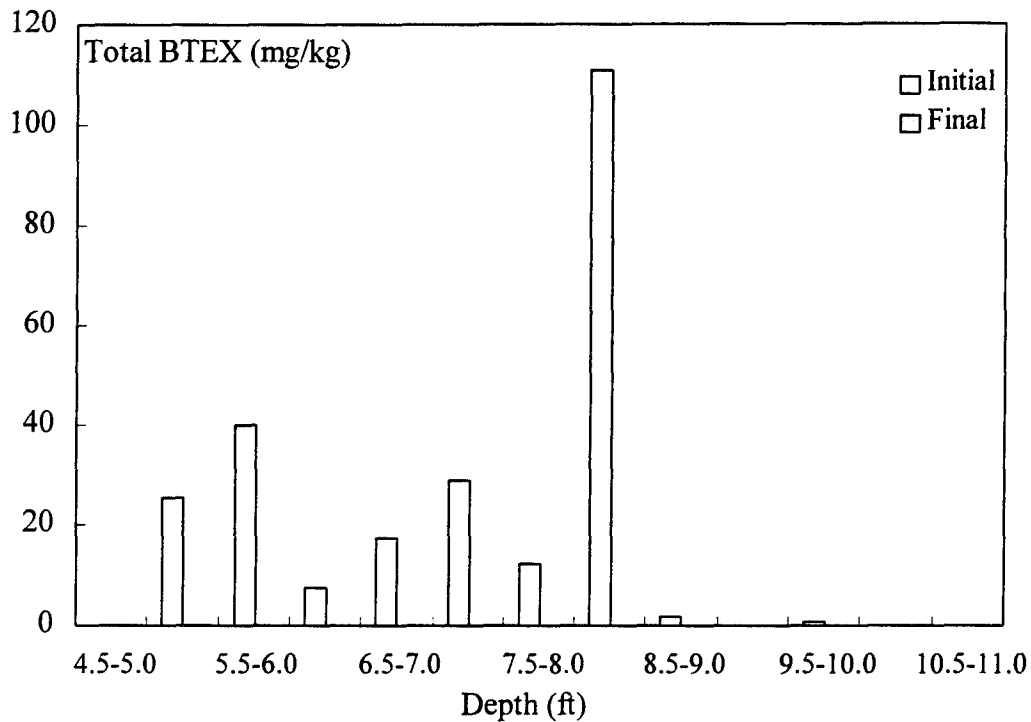
Figure 26: Initial and Final Average BTEX Soil Concentrations by Depth

4.6 Estimated Costs and Required Remediation Time

The following cost table was developed by Battelle project managers. It provides

a reference on the costs of a project of this scope. These cost tables are found in the

Eielson AFB project final report and developed assuming the remediation of a 5,000 yd^3

contaminated site.

Table 12: Estimated Remediation Time and Costs/Yd^3

Task	Control	Warm Water	Passive	Heat Tape
Concentration = 4,000 ppm				
Site Visit/Planning	5,000	5,000	5,000	5,000
Work Plan Preparation	6,000	6,000	6,000	6,000
Pilot Testing	27,000	27,000	27,000	27,000
Regulatory Approval	3,000	6,000	3,000	3,000
Full-Scale Construction				
Design	7,500	7,500	7,500	7,500
Drilling/Sampling	15,000	20,000[1]	15,000	15,000
Installation/Start Up	4,000	26,000	10,500	13,000
Monitoring	30,550	9,800	24,150	11,050
Power	13,160	9,800	9,660	17,000
Final Soil Sampling	13,500	13,500	13,500	13,500
Present Worth Cost/ yd^3	$23.37	$25.65	$23.24	$24.03
Remediation Time Required	9.4 yrs	2.8 yrs	6.9 yrs	3.4 yrs

[1]Requires installation and development of one water well.

The soil warming techniques used at Eielson AFB are comparable in cost to one another. However, by not warming a site, as shown by the control plot, remediation may take .5 to 3 times longer. The simple action of covering and insulating a site can reduce remediation time by several years.

Comparatively, soil venting techniques are inexpensive with costs ranging from $15 to 20/yd^3. If off-gas treatment is required, these costs will double. Costs for excavating of a contaminated site will range from $50 to $300/yd^3 depending on the transportation requirements. On-site incineration with a rotary kiln costs between $200 and $640/yd^3 (Lyman et al., 43,61,63).

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V. Conclusions and Recommendations

5.1 Conclusion on Efficacy of Soil Warming Techniques

Numerous soil warming techniques were discussed in this study. Three warming methodologies discussed were applied at the JP-4 remediation bioventing site at Eielson AFB. The Eielson AFB project was the first of its kind in operating a year-round bioremediation effort in a cold climate. This project and other studies have demonstrated that biodegradation does increase with temperature and that a minimal temperature exists for microbial activity to occur. Additionally, it was shown that bioremediation can be conducted year-round in cold climates and is not limited to a few months in the summer.

One soil warming technique, warm water, was effective in increasing soil temperatures but had a major drawback. The warm water method should only be used when moisture levels are low and the addition of water will not diminish microbial activity because of decreased O_2 availability, or when water will diffuse quickly through a site. The results of the Eielson project illustrate the need to consider a site's hydrogeology and its ability to handle increased water saturation. The most inexpensive and simplest warming technique are the passive methodologies. An inexpensive off-the-shelf plastic or fabric cover can increase soil temperatures in addition to preventing excess water from accumulating at the site; this was also effectively demonstrated at Eielson AFB. Not only will covering a site reduce the convective heat loss due to a cold wind, it also increases heat retention in the soil and dampens the diurnal temperature

fluctuation. This maintains a more consistent temperature for microbial activity to occur. Compared to the control plot, covering the soil increased average soil temperatures between 0.5 to 5.0 °C (see Table 6). Additionally, biodegradation rates were consistently higher at the passive warming plot, especially in comparison with the shallow and middle depths.

The other soil warming technique employed by the Eielson AFB project managers was heat tape. Heat tape was the most effective in maintaining higher soil temperatures and overcame high moisture levels. Biodegradation rates at this plot were 3 to 4 times higher than the passive warming and control plots and slightly higher than the warm water plot. Although it was comparable in cost per cubic yard to the other warming technique, it could be very expensive, depending on electricity costs. The digging, installation and equipment required for operation of electric heat tape could also be cost-prohibitive.

5.1.1 Effectiveness in Remediating JP-4 at Eielson AFB

The Eielson project managers reported positive results. Over the course of the project, they conclude that average respiration rates at the warm water, passive warming, control, and heat tape plots were 3.1, 1.3, 0.86, and 2.9 mg-hexane/kg-soil/day. These rates correspond to estimated hydrocarbon removal rates of 3400, 1400, 940, and 2100 mg/kg in the warm water, passive warming, control, and heat tape plots respectively. Given an average biodegradation rate of 2.5 mg/kg/day over the entire site, these values

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correspond to the bioremediation of approximately 9800 gallons of jet fuel (Battelle, 122). A breakdown of the estimated remediation time required by each technique is shown in Table 12. Time to remediate the control plot is 3 to 4 times longer than the warm water and heat tape methodologies. The trade-off between costs and remediation time is a project-specific issue depending upon many factors to include the contaminant's proximity and migratory risk to receptors. Nevertheless, the cost/yd^3 for temperature-enhanced bioventing projects is significantly lower than conventional excavation and off-site treatment.

5.2 Conclusions on Modeling Biodegradation

Several equations have been developed that estimate biodegradation rates based on the results of numerous projects. The equation published in the Bioventing Test Plan and Technical Protocol proves to be a simple and acceptable biodegradation calculation requiring little data. This equation and that published by Hinchee and Ong depend on many assumptions which may not account for all variables or model the complexities at a site. There are still some unanswered questions. For example, what is the effect of high soil moisture levels on microbial respiration? Concerning the predictive van't Hoff-Arrhenius equation, do higher soil moisture, annual freezing, and the trenches installed at two plots alter the activation energy and frequency factor that would normally be observed? Given that trench digging and backfilling altered the kinetics and

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contamination distribution at those locations, did it also affect the contaminant flow and direction?

Modeling the temperature-biodegradation relationship by the van't Hoff-Arrhenius equation was valid for only the warm water and passive warming plots. This study demonstrated that using data averaged over the entire site and including all test plots may portray an acceptable result; however, the results can be very different when data from individual plots is examined separately. For example, the plots developed by Dr. Sayles convey that the application of the van't Hoff-Arrhenius equation is scientifically valid unless you break down and examine the individual data applicable to each experimental test plot. Additionally, biodegradation rates varied according to depth since contamination was not homogeneously distributed vertically. Comparisons made with published research using the van't Hoff-Arrhenius relationship showed some variation and illustrated the need for continued study.

5.3 Recommendations for Future Research

A better understanding and modeling of chemical kinetics of biodegradation as a function of temperature should be addressed. The van't Hoff-Arrhenius equation may be too simple to accurately model what is occurring, especially in a cold environment. Studies that measure the amount of active biomass and contaminant concentration would be worthwhile in determining how these factors are accounted for in the frequency factor term. This research should include how the van't Hoff-Arrhenius relationship changes as

the contaminant concentration and microbial respiration decrease. Additionally, for cold climate applications how does the amount of active microbial biomass change on an annual basis taking into consideration freezing temperatures and increased soil moisture. Freezing temperatures significantly reduce microbial activity and a better understanding of this relationship under field conditions is warranted.

Following the conclusion of the jet fuel bioremediation project at Hill AFB, Utah, which used solar warming techniques, the data should be analyzed and compared to the results obtained here. Additionally, comparisons may be made with other bioventing applications performed in Alaska and the colder regions of Canada where soil temperature data is available. Another question for cold climate applications is the determination of a 'window of opportunity' for bioremediation to occur. What is the remediation effectiveness of heating the soil year-round? Does remediation occur in the winter months and are the results sufficient to justify the costs? Can this 'window of opportunity' be widened to those months when costs are justified and results sufficient?

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Vita

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He entered the Air Force in July 1982 as a cryptologic linguist. Following language and

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Following Squadron Officers School, in May 1994 he entered the School of

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APPENDIX A: Plot Average Temperatures [°C]

Date	Warm Water 5.25/7.0'	Warm Water 4.0/4.25'	Warm Water 2.0/2.5'	Passive Warming 5.25/7.0'	Passive Warming 4.0/4.25'	Passive Warming 2.0/2.5'	Heat Tape 7.5'	Heat Tape 4.5'	Heat Tape 2.5'	Control 5.25/7.5'	Control 4.25/4.5'	Control 2.0/2.5'
8/28/91	10.3	11.8	13.1	9.0	10.2	10.8				9.5	10.9	11.1
8/30/91	10.8	12.7	12.1	8.1	9.2	9.2				8.4	9.7	9.8
9/1/91	10.7	12.7	14.6	7.8	8.6	8.9				8.2	9.2	9.5
9/3/91	10.9	12.8	14.3	7.7	8.4	9.0				8.0	9.1	9.5
9/5/91	10.9	12.6	12.9	7.6	8.4	9.2				8.0	9.2	9.8
9/7/91	11.0	12.8	14.0	7.6	8.6	9.6				8.3	9.4	10.1
9/9/91	10.9	12.3	12.9	7.5	8.5	9.1				8.2	9.3	9.6
9/11/91	10.8	12.3	13.3	7.4	8.3	8.9				8.0	9.1	9.5
9/13/91	10.6	12.3	13.2	7.4	8.3	8.9				8.1	9.1	9.4
9/15/91	10.5	11.9	12.6	7.1	8.2	8.7				8.0	8.9	9.3
9/17/91	9.9	11.4	11.8	7.1	8.1	8.6				7.9	8.9	9.2
9/19/91	10.0	11.3	11.7	7.0	7.9	8.4				7.9	8.8	9.0
9/21/91	9.9	11.2	11.5	7.0	8.0	8.1				7.9	8.7	8.7
9/23/91	10.4	11.6	12.0	7.3	8.0	7.9				7.9	8.4	8.6
9/25/91	9.9	10.8	10.9	6.7	7.4	7.5				7.6	8.1	8.1
9/27/91	10.3	11.3	11.6	6.7	7.5	7.3				7.5	8.0	7.6
9/29/91	9.6	10.5	10.4	6.5	7.4	7.1				7.3	7.8	7.6
10/1/91	10.0	10.9	11.1	6.5	7.1	6.6				7.2	7.5	7.2
10/3/91	9.1	9.9	9.8	6.3	6.9	6.5				7.0	7.1	6.7
10/5/91	9.8	10.6	10.7	6.2	6.8	6.4				7.0	6.9	6.4
10/7/91	9.7	10.4	10.5	6.0	6.6	6.2				6.7	6.6	6.1
10/9/91	8.8	9.4	8.9	5.5	6.5	6.0				6.5	6.2	5.5
10/11/91	9.5	10.2	10.0	5.5	6.4	5.6				6.3	5.7	4.7
10/13/91	9.4	9.7	9.9	5.5	6.1	5.2				5.6	5.1	4.0
10/15/91	8.4	9.2	7.9	5.0	5.7	4.4				5.5	4.6	3.4
10/17/91	8.3	8.9	7.6	4.7	5.3	4.0				5.2	4.1	2.8
10/19/91	9.1	9.8	9.2	4.8	5.3	3.8				4.9	3.9	2.6
10/21/91	7.8	8.3	6.9	4.4	5.0	3.5				4.6	3.5	2.3
10/23/91	8.7	9.1	8.7	5.0	4.7	3.2				4.3	3.2	2.1
10/25/91	8.8	9.4	9.2	4.9	4.5	3.2				4.1	3.0	2.0
10/27/91	8.9	9.7	9.7	4.8	4.4	3.2				3.9	2.8	1.8
10/29/91	9.0	9.9	9.9	4.7	4.3	2.9				3.7	2.7	1.7
10/31/91	9.2	9.9	10.1	4.5	4.1	2.5				3.5	2.5	1.6
11/2/91	9.3	10.1	9.8									
11/4/91	9.2	9.8	9.4									
11/6/91	9.2	9.7	9.8									
11/8/91	9.0	9.6	9.9									
11/10/91	8.8	9.4	9.8									
11/12/91	9.3	10.3	9.8	3.5	2.8	1.2				2.7	1.6	0.5
11/14/91	9.5	10.2	9.4	3.5	2.8	1.0				2.4	1.1	0.3
11/16/91	9.7	10.4	9.9									
11/18/91	8.7	9.3	8.5	3.3	2.6	0.9				2.4	1.3	0.2
11/20/91	8.7	9.5	9.5	3.1	2.4	0.8				2.2	1.1	0.0
11/22/91	8.9	9.8	10.2	3.0	2.4	0.7				2.1	1.0	-0.1
11/24/91	9.4	10.5	10.7	2.8	2.1	0.5				1.9	0.8	-0.3

	Warm Water			Passive Warming			Heat Tape			Control		
Date	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	7.5'	4.5'	2.5'	5.25/ 7.5'	4.25/ 4.5'	2.0/ 2.5'
11/26/91	9.6	10.6	10.8	2.8	2.1	0.5				1.9	0.8	-0.3
11/28/91	9.1	10.2	9.3	2.6	2.0	0.4				1.8	0.7	-0.3
11/30/91	9.5	10.4	9.8	2.5	1.8	0.3				1.6	0.6	-0.5
12/2/91	9.8	10.6	11.0									
12/4/91	9.5	10.4	10.1	2.4	1.7	0.4				1.6	0.6	-0.3
12/6/91	9.0	9.7	9.2	2.3	1.7	0.3				1.6	0.5	-0.4
12/8/91	9.3	10.1	9.7	2.1	1.4	0.0				1.1	0.2	-0.7
12/10/91	8.6	9.3	8.7	2.0	1.3	0.0				1.1	0.2	-0.7
12/12/91	8.6	9.1	8.5	2.1	1.4	0.1				1.2	0.2	-0.7
12/14/91	9.0	9.8	9.4	1.9	1.3	0.0				1.0	0.0	-0.9
12/16/91	8.3	9.0	8.5	1.8	1.2	-0.1				1.1	0.1	-0.7
12/18/91	9.0	9.7	9.3	1.9	1.3	0.1				1.2	0.3	-0.7
12/20/91	9.0	9.7	9.1	1.9	1.3	0.1				1.1	0.3	-0.6
12/22/91	8.2	8.8	8.0	2.0	1.4	0.1				1.1	0.3	-0.6
12/24/91	8.5	8.8	8.0	1.7	1.2	0.0				1.0	0.1	-0.7
12/26/91	8.7	9.5	8.9	1.6	1.0	-0.2				0.8	0.0	-0.8
12/28/91	8.0	8.6	7.7	1.5	0.9	-0.2				0.8	-0.1	-0.9
12/30/91	8.7	9.3	8.9	1.6	1.0	-0.2				0.8	0.0	-0.8
1/1/92	8.6	9.3	8.9	1.5	0.9	-0.2				0.7	-0.1	-0.8
1/3/92	8.6	9.3	9.1	1.5	0.9	-0.2				0.7	-0.1	-0.9
1/5/92	8.0	8.6	8.0	1.4	0.9	-0.3				0.7	-0.1	-1.0
1/7/92	7.9	8.6	7.9	1.4	0.9	-0.3				0.7	-0.1	-0.9
1/9/92	7.9	8.6	7.9	1.4	0.8	-0.3				0.7	-0.2	-1.0
1/11/92	7.9	8.6	7.8	1.2	0.7	-0.3				0.6	-0.3	-1.1
1/13/92	8.7	9.4	9.2	1.3	0.8	-0.3				0.7	-0.1	-1.0
1/15/92	7.9	8.6	8.1	1.1	0.6	-0.5				0.4	-0.3	-1.1
1/17/92	8.5	9.2	9.1	1.1	0.6	-0.4				0.4	-0.3	-1.1
1/19/92	8.0	8.8	8.5	1.1	0.7	-0.4				0.5	-0.3	-1.1
1/21/92	8.7	9.5	9.5	1.2	0.7	-0.3				0.5	-0.2	-1.0
1/23/92	8.7	9.6	9.5	1.2	0.8	-0.3				0.6	-0.2	-0.9
1/25/92	8.7	9.6	9.5	1.0	0.5	-0.5				0.4	-0.3	-1.1
1/27/92	8.5	9.3	9.1	1.0	0.6	-0.5				0.4	-0.3	-1.1
1/29/92	7.9	8.7	8.4	0.8	0.3	-0.6				0.2	-0.5	-1.3
1/31/92	8.5	9.3	9.2	0.9	0.5	-0.6				0.3	-0.4	-1.3
2/2/92	8.6	9.3	9.2	0.8	0.4	-0.6				0.3	-0.5	-1.4
2/4/92	8.1	9.0	8.7	0.8	0.3	-0.6				0.2	-0.5	-1.5
2/6/92	8.4	9.3	8.9	0.8	0.3	-0.7				0.1	-0.6	-1.6
2/8/92	8.6	9.2	8.9	0.6	0.3	-0.7				0.1	-0.6	-1.6
2/10/92	9.1	9.9	10.3									
2/12/92	9.3	10.1	10.4									
2/14/92	8.6	9.4	9.2	0.7	0.3	-0.6				0.2	-0.5	-1.3
2/16/92	8.6	9.4	9.3	0.8	0.4	-0.5				0.3	-0.5	-1.2
2/18/92	8.7	9.5	9.5	0.8	0.4	-0.5				0.3	-0.4	-1.2
2/20/92	8.6	9.7	10.0	0.7	0.3	-0.6				0.2	-0.5	-1.8
2/22/92	9.0	10.5	11.4	0.7	0.3	-0.6				0.2	-0.5	-1.4

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	Warm Water			Passive Warming			Heat Tape			Control		
Date	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	7.5'	4.5'	2.5'	5.25/ 7.5'	4.25/ 4.5'	2.0/ 2.5'
2/24/92	9.6	11.5	12.6	0.6	0.2	-0.7				0.1	-0.6	-1.6
2/26/92	10.9	13.1	13.7	0.6	0.1	-0.8				0.1	-0.7	-1.6
2/28/92	11.5	13.6	14.4	0.5	0.1	-0.9				0.1	-0.8	-1.8
3/1/92	12.4	14.4	15.8	1.0	0.5	-0.4				0.3	-0.4	-1.5
3/3/92	12.7	14.7	16.2	0.7	0.3	-0.6				0.1	-0.6	-1.6
3/5/92	13.3	15.2	16.4	0.7	0.3	-0.7				0.2	-0.6	-1.7
3/7/92	13.7	15.5	16.3	0.6	0.2	-0.3				-0.1	-0.8	-1.9
3/9/92	13.9	15.5	16.2	0.2	-0.1	-1.1				-0.4	-1.0	-2.3
3/11/92	13.8	15.5	16.7	0.2	-0.1	-1.0				-0.3	-1.0	-2.1
3/13/92	14.0	15.6	17.3	0.3	-0.1	-1.0				-0.3	-1.0	-1.9
3/15/92	14.3	16.2	17.4	0.4	0.0	-0.8				-0.2	-0.8	-1.6
3/17/92	14.6	16.5	17.2	0.2	-0.2	-1.0				-0.4	-1.0	-1.8
3/19/92	15.0	16.8	17.2	0.4	0.1	-0.8				-0.1	-0.7	-1.4
3/21/92	15.4	17.1	17.8	0.1	-0.2	-1.0				-0.4	-0.9	-1.6
3/23/92	15.7	17.5	18.3	0.2	-0.2	-0.9				-0.3	-0.9	-1.5
3/25/92	16.0	17.8	18.5	0.1	-0.2	-1.0				-0.4	-1.0	-1.5
3/27/92	16.3	17.9	19.0	0.2	-0.2	-0.9				-0.4	-0.9	-1.4
3/29/92	16.5	18.3	19.2	0.3	-0.1	-0.9				-0.3	-0.8	-1.2
3/31/92	16.8	18.6	19.5	0.3	-0.1	-0.9				-0.3	-0.7	-1.2
4/2/92	17.0	18.6	20.3									
4/4/92	17.2	18.9	19.4	0.1	-0.3	-1.0				-0.4	-0.9	-1.4
4/6/92	17.5	19.1	19.7	0.3	-0.1	-0.8				-0.3	-0.7	-1.2
4/8/92	17.7	19.2	19.6	0.1	-0.2	-0.9				-0.4	-0.9	-1.3
4/10/92	17.6	19.2	19.4	0.0	-0.3	-1.0				-0.4	-0.9	-1.3
4/12/92	17.7	19.2	19.4	0.2	-0.1	-0.8				-0.2	-0.7	-1.1
4/14/92	17.9	19.2	19.0	0.2	-0.2	-0.9				-0.3	-0.8	-1.1
4/16/92	17.6	18.8	18.2	-0.1	-0.2	-1.0				-0.4	-0.9	-1.3
4/18/92	17.5	18.5	17.5	0.1	-0.3	-1.0				-0.5	-0.9	0.0
4/20/92	17.2	17.7	16.8	0.2	-0.2	-0.8				-0.5	-1.2	-1.2
4/22/92	16.7	17.4	17.6	0.1	-0.2	-0.8				-0.3	-0.7	-1.0
4/24/92	16.4	17.4	18.2	0.0	-0.2	-0.6				-0.4	-0.8	-1.2
4/26/92	16.3	17.5	17.5	0.0	-0.2	-0.8				-0.3	-0.7	-1.0
4/28/92	16.3	17.6	17.2	0.0	-0.1	-0.7				-0.3	-0.7	-0.9
4/30/92	16.7	18.4	16.5	-0.1	0.0	-0.6				-0.3	-0.6	-0.9
5/2/92	16.9	18.0	16.3	-0.1	-0.1	-0.4				-0.4	-0.8	-1.0
5/4/92	16.7	17.8	17.3	0.0	-0.2	-0.2				-0.4	-0.8	-1.0
5/6/92	16.4	17.6	17.9	0.2	0.3	0.2				-0.3	-0.8	-0.9
5/8/92	16.1	17.4	17.4	0.0	0.2	1.2				-0.4	-0.8	-1.0
5/10/92	15.9	17.0	17.6	0.1	0.5	1.3				-0.3	-0.8	-0.9
5/12/92	15.7	16.7	16.0	0.1	0.5	1.6				-0.3	-0.7	-0.9
5/14/92	14.7	15.9	15.5	0.6	0.8	1.9				-0.4	-0.8	-0.9
5/16/92	14.8	15.7	15.2	0.7	1.0	2.9				-0.4	-0.9	-0.9
5/18/92	14.4	15.3	14.9	0.9	1.5	2.7				-0.3	-0.7	-0.9
5/20/92	14.1	15.0	15.0	1.2	1.9	3.0				-0.3	-0.7	-0.9
5/22/92	13.9	15.0	15.2	1.4	2.3	4.4				-0.2	-0.6	-0.8

	Warm Water			Passive Warming			Heat Tape			Control		
Date	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	7.5'	4.5'	2.5'	5.25/ 7.5'	4.25/ 4.5'	2.0/ 2.5'
5/24/92	13.8	15.0	15.4	1.7	2.9	6.8				-0.2	-0.7	-0.8
5/26/92	13.6	15.0	15.7	1.9	3.7	9.3				-0.4	-0.8	-0.9
5/28/92	13.8	15.4	16.6	2.5	4.9	11.4				-0.3	-0.7	-0.8
5/30/92	14.0	15.7	16.6	3.1	6.0	12.6				-0.4	-0.7	-0.7
6/1/92	14.1	16.0	18.0	3.8	7.0	13.7				-0.2	-0.5	-0.5
6/3/92	14.5	16.9	19.5	4.4	7.6	14.4				-0.3	-0.6	0.0
6/5/92	15.1	17.7	20.4	5.0	8.3	14.5				-0.2	-0.4	0.5
6/7/92	15.8	18.7	21.1	5.6	8.9	15.0				0.2	0.2	1.2
6/9/92	16.7	20.0	22.9	6.3	9.7	15.6				1.1	0.9	1.8
6/11/92	17.6	21.1	23.1	6.3	9.7	16.4				1.1	0.8	4.2
6/13/92	18.4	21.7	23.2	6.8	10.4	17.8				1.7	1.3	5.7
6/15/92	19.0	22.2	23.4	7.6	11.6	19.3				2.7	2.2	7.8
6/17/92	18.3	22.0	23.9	8.2	12.2	18.8				3.3	2.7	8.7
6/19/92	18.9	22.3	24.6	8.7	12.6	17.6				4.1	4.2	8.7
6/21/92	19.0	22.4	25.2	9.1	12.7	18.2				4.4	5.0	9.4
6/23/92	19.4	23.9	29.2									
6/25/92	19.6	21.9	22.2									
6/27/92	19.4	21.2	20.8									
6/29/92	18.2	18.5	17.9									
7/1/92	17.4	18.3	18.3	9.8	13.2	20.0				5.9	8.2	11.1
7/3/92	17.1	18.1	18.1	10.3	13.8	20.3				6.7	9.2	12.0
7/5/92	16.8	17.7	17.8	10.5	14.3	21.3				6.9	9.6	12.5
7/7/92	16.6	17.5	17.6	11.0	16.1	21.9				7.4	10.3	13.2
7/9/92	16.4	17.3	17.3	11.2	15.0	21.4				7.5	10.4	13.0
7/11/92	16.2	17.0	17.0	11.5	15.2	21.3				7.8	10.7	13.1
7/13/92	15.7	16.6	16.9	11.8	15.4	21.2				8.2	11.1	13.5
7/15/92	15.9	16.7	17.0	12.0	16.7	20.6				8.6	11.4	13.7
7/17/92	15.7	16.6	17.0	12.1	16.7	20.3				8.7	11.4	13.9
7/19/92	15.3	16.3	17.0	12.1	16.5	20.2				8.7	11.5	13.9
7/21/92	15.4	16.5	17.3	12.4	16.8	20.5				9.1	11.8	14.2
7/23/92	15.5	16.7	17.7	12.6	16.7	20.5				9.3	11.9	14.2
7/25/92	15.4	16.7	17.6	12.7	16.8	20.7				9.5	12.0	14.3
7/27/92	14.9	16.2	17.3	12.8	16.9	20.7				9.7	12.1	14.5
7/29/92	15.7	17.1	18.0	13.0	17.0	20.4				10.0	12.4	14.5
7/31/92	15.7	17.2	17.9	13.1	16.9	20.2				10.1	12.4	14.6
8/2/92	15.9	17.2	17.7	13.2	17.0	20.2				10.3	12.6	14.7
8/4/92	16.0	17.2	17.5	13.3	16.9	19.9				10.4	12.7	14.6
8/6/92	15.9	17.1	17.4	13.3	16.9	19.6				10.6	12.7	14.6
8/8/92	16.0	17.0	17.3	13.5	16.9	19.6				10.7	12.9	14.7
8/10/92	16.0	17.0	17.2	13.6	16.9	18.8				11.0	13.0	14.3
8/12/92	15.9	16.8	16.9	13.4	16.6	18.5				10.8	12.7	14.1
8/14/92	15.6	16.6	16.7	13.3	16.5	18.2				10.9	12.7	14.1
8/16/92	15.6	16.4	16.4	13.3	16.3	18.0				10.8	12.5	13.7
8/18/92	15.3	16.2	16.2	13.1	16.0	17.3				10.7	12.1	13.1
8/20/92	15.1	15.9	16.0	13.1	15.7	16.6				10.5	11.7	12.4

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Date	Warm Water 5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	Passive Warming 5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	Heat Tape 7.5'	4.5'	2.5'	Control 5.25/ 7.5'	4.25/ 4.5'	2.0/ 2.5'
8/22/92	15.0	15.8	15.9	12.9	15.3	16.4				10.4	11.4	12.3
8/24/92	14.9	15.7	15.7	12.8	15.1	16.5				10.2	11.3	12.4
8/26/92	14.8	15.6	15.7	12.8	15.0	16.6				10.1	11.4	12.4
8/28/92	14.7	15.4	15.5	12.6	14.9	16.0				10.1	11.2	12.0
8/30/92	14.6	15.3	15.3	12.5	14.7	15.8				10.1	11.1	11.8
9/1/92	14.4	15.2	15.0	12.4	14.4	15.2				9.7	10.8	11.5
9/3/92	14.3	15.0	14.8	12.4	14.2	14.7				9.6	10.6	11.0
9/5/92	14.1	14.9	14.6	12.2	13.8	14.3				9.5	10.3	10.6
9/7/92	14.0	14.7	14.4	12.0	13.5	14.0				9.3	10.0	10.3
9/9/92	13.6	14.4	14.0	11.8	13.3	13.7				9.1	9.7	10.0
9/11/92	13.4	14.1	13.7	11.7	13.1	12.7				9.0	9.5	9.2
9/13/92	13.3	14.0	13.2	11.2	12.5	10.8				8.6	8.6	7.9
9/15/92	12.8	13.5	12.3	10.8	11.7	9.2				8.2	7.8	6.8
9/17/92	12.7	13.1	12.2	10.6	11.1	8.0				7.7	6.8	5.8
9/19/92	12.4	13.0	12.2	10.2	10.0	7.9				7.2	6.3	5.1
9/21/92	12.3	12.9	12.6	9.8	9.5	7.6				6.8	5.9	4.7
9/23/92	13.6	15.0	15.5	9.2	8.9	6.2				6.1	5.1	4.0
9/25/92	14.0	15.7	16.2	9.1	8.8	6.4				6.3	5.5	4.0
9/27/92	15.1	17.4	18.2	8.7	8.4	6.6				5.9	5.0	3.5
9/29/92	16.2	18.4	17.8	8.5	8.1	6.1				5.7	4.8	3.3
10/1/92	16.1	18.0	17.0	8.1	7.7	5.9				5.6	4.8	3.6
10/3/92	16.5	17.8	16.8	8.0	7.6	5.7	7.8	7.3	5.2	5.5	4.6	3.4
10/5/92	16.2	14.8	15.8	7.7	7.2	5.1	7.8	6.9	5.0	5.4	4.4	3.2
10/7/92	15.9	16.9	15.8	7.4	6.9	4.6	7.5	6.7	4.8	5.1	4.1	2.9
10/9/92	15.7	16.7	15.9	7.0	6.6	5.0	7.4	6.4	4.7	5.0	3.9	2.7
10/11/92	15.7	16.8	16.5	6.9	6.5	5.2	7.2	6.3	4.7	4.9	3.8	2.6
10/13/92	15.9	17.3	16.9	6.8	6.4	5.1	7.3	6.3	4.9	4.7	3.6	2.5
10/15/92	16.2	17.5	17.0	6.6	6.2	4.8	7.2	6.3	5.3	4.4	3.4	2.2
10/17/92	16.3	17.6	16.6	6.5	6.1	4.9	6.9	6.2	5.8	4.4	3.4	2.1
10/19/92	16.4	17.5	16.5	6.6	6.1	4.6	6.9	6.4	6.5	4.2	3.2	2.1
10/21/92	15.8	16.9	15.0	6.2	5.7	4.0	7.0	6.7	7.1	4.1	3.1	2.0
10/23/92	15.9	16.8	15.1	6.1	5.5	3.9	6.8	6.9	7.5	4.0	3.0	1.9
10/25/92	15.6	16.8	15.0	6.0	5.3	3.7	6.9	7.2	8.1	3.8	2.9	1.7
10/27/92	16.2	17.1	15.6	5.7	5.1	3.4	7.2	7.7	8.7	3.8	2.8	1.6
10/29/92	16.2	17.0	15.7	5.6	4.9	3.5	7.1	7.8	8.7	3.8	2.6	1.3
11/1/92	16.1	16.7	14.6	5.4	4.8	3.1	7.1	7.9	8.9	3.7	2.5	1.2
11/3/92	15.7	16.0	13.3	5.2	4.5	2.5	7.1	8.0	9.2	3.6	2.4	1.1
11/5/92	15.4	15.4	12.6	5.0	4.2	2.1	6.9	8.1	9.4	3.5	2.3	1.0
11/7/92	15.0	14.7	12.0	4.9	4.1	1.9	7.1	8.4	9.8	3.2	2.3	0.9
11/9/92	14.5	14.1	11.9	4.7	3.8	1.7	7.2	8.5	10.1	3.1	2.2	0.9
11/11/92	14.1	14.0	12.7	4.5	3.6	1.7	7.3	8.7	10.0	3.1	2.1	0.8
11/13/92	13.8	14.3	13.5	4.3	3.5	1.5	7.3	8.6	9.8	3.0	2.0	0.9
11/15/92	13.7	14.6	14.0	4.2	3.4	1.4	7.3	8.7	9.8	2.9	2.0	0.8
11/17/92	13.9	14.9	14.5	4.0	3.2	1.3	7.4	8.8	9.9	2.8	1.9	0.8
11/19/92	13.9	15.1	14.7	3.9	3.0	1.3	7.4	8.8	10.2	2.7	1.9	0.7

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	Warm Water			Passive Warming			Heat Tape			Control		
Date	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	7.5'	4.5'	2.5'	5.25/ 7.5'	4.25/ 4.5'	2.0/ 2.5'
11/21/92	14.1	15.4	15.0	3.8	3.0	1.3	7.4	8.9	10.4	2.6	1.8	0.7
11/23/92	14.3	15.6	15.1	3.7	2.9	1.3	7.5	9.0	10.6	2.6	1.9	0.7
11/25/92	14.4	15.7	14.6	3.4	2.7	1.4	7.5	9.2	10.8	2.5	1.7	0.6
11/27/92	14.3	15.4	14.3	3.5	2.6	1.3	7.7	9.2	10.9	1.7	1.7	0.6
11/29/92	14.3	15.4	14.3	3.0	2.5	1.2	7.6	9.3	11.1	1.6	1.6	0.4
12/1/92	14.2	15.3	14.2	3.2	2.5	1.4	7.6	9.5	11.3	1.6	1.6	0.4
12/3/92	14.0	15.0	13.9	3.1	2.4	1.0	7.7	9.5	11.4	1.4	1.4	0.3
12/5/92	13.8	14.7	13.1	3.1	2.4	1.2	7.9	9.7	11.5	1.5	1.4	0.3
12/7/92	13.4	14.1	12.8	3.0	2.3	1.1	7.9	9.7	11.5	1.4	1.3	0.2
12/9/92	13.2	13.8	12.7	2.9	2.2	1.0	8.0	9.9	11.7	1.4	1.2	0.1
12/11/92	13.0	13.8	12.9	2.9	2.2	0.9	7.8	9.9	11.7	1.3	1.2	0.1
12/13/92	12.9	13.8	12.8	2.5	2.1	0.9	8.0	10.1	12.0	1.2	1.0	-0.2
12/15/92	12.9	13.8	13.0	2.7	2.0	0.8	8.0	10.1	11.9	1.3	1.1	-0.1
12/17/92	12.9	14.0	13.4	2.5	1.9	0.8	8.2	10.2	11.7	1.2	1.0	-0.2
12/19/92	13.0	14.1	13.8	2.5	1.8	0.8	8.2	10.3	11.7	1.2	0.9	-0.2
12/21/92	13.3	14.5	14.1	2.4	1.8	0.7	8.2	10.1	11.5	1.2	0.9	-0.4
12/23/92	13.4	14.6	14.7	2.5	1.8	0.7	8.0	10.1	11.4	1.2	1.0	-0.3
12/25/92	13.5	15.2	14.8	2.4	1.7	0.6	8.0	10.2	11.4	1.1	0.9	-0.4
12/27/92	13.8	15.4	15.0	2.4	1.8	0.5	8.1	10.1	11.4	1.1	0.9	-0.3
12/29/92	13.9	15.5	15.6	2.2	1.6	0.3	8.2	10.2	11.7	0.9	0.9	-0.4
12/31/92	14.1	15.9	15.0	2.1	1.5	0.1	8.4	10.2	11.8	0.9	0.9	-0.2
1/2/93	14.2	15.8	15.4	2.1	1.5	0.0	8.3	10.2	11.5	0.9	0.8	-0.5
1/4/93	14.2	15.8	15.6	2.1	1.5	-0.1	8.3	10.3	11.4	0.8	0.8	-0.5
1/6/93	14.6	16.1	15.5	2.1	1.5	0.4	8.4	10.2	11.5	0.8	0.7	-0.4
1/8/93	14.8	16.2	15.7	2.0	1.4	0.4	8.3	10.2	11.6	0.8	0.7	-0.4
1/10/93	15.2	16.7	16.5	2.1	1.5	0.5	8.4	10.2	11.7	0.9	0.8	-0.3
1/12/93	15.3	17.0	16.5	2.0	1.4	0.4	8.4	10.3	12.0	0.7	0.8	-0.3
1/14/93	15.7	17.4	17.1	2.0	1.4	0.4	8.4	10.3	12.0	0.8	0.8	-0.3
1/16/93	16.0	17.8	17.3	1.9	1.3	0.4	8.4	10.4	12.2	0.8	0.7	-0.4
1/18/93	16.3	18.2	18.0	1.9	1.4	0.3	8.4	10.5	12.3	0.7	0.6	-0.4
1/20/93	16.8	18.7	18.1	1.6	1.1	0.7	8.4	10.5	12.4	0.8	0.6	-0.4
1/22/93	17.2	19.0	17.9	1.9	1.4	0.5	8.6	10.7	12.4	0.8	0.7	-0.5
1/24/93	17.6	19.0	17.6	1.8	1.3	0.4	8.6	10.7	12.5	0.9	0.6	-0.6
1/26/93	17.2	18.7	17.1	1.7	1.2	0.3	8.5	10.8	12.5	0.7	0.4	-0.9
1/28/93	17.1	18.4	16.2	1.6	1.0	0.2	8.4	10.8	12.5	0.5	0.3	-1.0
1/30/93	16.6	17.6	15.2	1.7	1.1	0.2	8.3	10.9	12.2	0.6	0.3	-1.0
2/1/93	16.2	16.9	14.3	1.6	1.1	0.2	8.4	10.8	11.7	0.7	0.4	-0.9
2/3/93	15.7	16.3	13.4	1.5	1.0	0.2	8.3	10.7	11.2	0.6	0.3	-1.1
2/5/93	14.8	15.0	11.7	1.4	0.9	0.1	8.3	10.5	10.6	0.4	0.3	-1.2
2/7/93	14.3	14.1	11.4	1.4	0.9	0.1	8.3	10.3	10.4	0.4	0.2	-1.2
2/9/93	14.0	14.0	12.1	1.4	0.9	0.1	8.2	10.2	10.5	0.4	0.2	-1.3
2/11/93	14.0	14.1	12.5	1.4	0.8	0.3	8.4	10.3	10.6	0.3	0.2	-1.3
2/13/93	13.9	14.3	13.1	1.3	0.8	0.0	8.1	10.0	10.2	0.2	0.2	-1.4
2/15/93	14.0	14.6	13.5	1.3	0.7	0.0	8.1	10.0	10.1	0.2	0.2	-1.3
2/17/93	14.1	14.8	13.9	1.2	0.8	0.1	8.2	10.0	10.1	0.2	0.2	-1.2

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	Warm Water			Passive Warming			Heat Tape			Control		
	5.25/	4.0/	2.0/	5.25/	4.0/	2.0/				5.25/	4.25/	2.0/
Date	7.0'	4.25'	2.5'	7.0'	4.25'	2.5'	7.5'	4.5'	2.5'	7.5'	4.5'	2.5'
2/19/93	14.2	15.1	14.5	1.2	0.7	0.0	8.2	9.9	10.1	0.2	0.2	-1.1
2/21/93	14.3	15.7	15.4	1.2	0.8	0.0	8.2	9.9	10.2	0.3	0.2	-1.0
2/23/93	14.2	15.6	14.7	1.2	0.8	0.0	8.2	9.8	10.3	0.2	0.2	-0.9
2/25/93	14.2	15.2	14.1	1.2	0.7	0.0	8.2	9.9	10.6	0.2	0.2	-0.9
2/27/93	13.7	14.6	13.2	1.2	0.7	0.0	8.2	10.0	11.0	0.2	0.2	-0.9
3/1/93	13.3	14.0	12.3	1.1	0.7	0.0	7.9	10.1	11.4	0.2	0.2	-0.9
3/3/93	12.9	13.4	11.5	1.1	0.6	0.0	8.0	10.2	11.7	0.2	0.1	-1.0
3/5/93	12.4	12.8	11.6	1.1	0.6	-0.2	8.2	10.3	12.0	0.2	0.0	-1.1
3/7/93	12.3	13.0	12.0	1.0	0.6	0.0	8.1	10.4	12.2	0.1	0.0	-1.1
3/9/93	12.4	13.1	12.4	1.0	0.6	-0.1	8.1	10.6	12.4	0.1	0.0	-1.2
3/11/93	12.5	13.4	13.0	1.1	0.6	-0.2	7.9	10.7	12.5	0.1	0.0	-1.2
3/13/93	12.7	13.8	13.5	0.9	0.5	-0.2	7.9	10.7	12.6	0.1	0.2	-1.0
3/15/93	13.5	14.5	14.7	1.1	0.6	0.0	8.0	10.8	12.4	0.2	0.0	-1.2
3/17/93	13.2	14.8	15.2	0.9	0.5	-0.2	7.9	10.8	12.4	0.0	0.0	-1.3
3/19/93	13.7	15.9	16.7	0.9	0.5	-0.2	8.1	10.8	12.5	0.1	0.0	-1.1
3/21/93	14.5	17.0	17.8	0.9	0.5	-0.2	8.2	10.9	12.6	0.3	0.0	-1.0
3/23/93	14.6	16.9	16.8	0.8	0.5	-0.2	8.3	11.0	12.7	0.0	0.1	-0.9
3/25/93	14.5	16.4	15.7	0.9	0.6	-0.1	8.3	10.9	12.7	0.1	0.1	-0.8
3/27/93	14.0	15.6	14.4	0.9	0.5	-0.3	8.5	11.0	12.8	-0.1	0.1	-0.9
3/29/93	13.4	14.7	13.2	0.8	0.4	-0.2	8.2	11.0	13.0	0.0	0.1	-0.9
3/31/93	12.9	14.0	12.3	0.8	0.4	-0.1	8.5	11.2	13.2	0.0	-0.1	-0.9
4/2/93	12.3	13.0	11.3	0.6	0.3	-0.7	8.4	11.3	13.3	-0.2	-0.2	-0.9
4/4/93	10.8	12.6	10.7	0.6	0.2	-0.7	8.3	11.1	13.2	-0.1	-0.2	-0.8
4/6/93	11.5	11.9	10.4	0.6	0.2	0.2	8.3	11.2	13.1	-0.2	-0.2	-0.8
4/8/93	11.1	11.6	10.3	0.6	0.2	0.2	8.4	11.3	13.2	-0.1	-0.3	-0.8
4/10/93	10.8	11.1	9.7	0.5	0.1	-0.1	8.4	11.3	13.0	-0.2	-0.9	-0.9
4/12/93	10.4	10.6	9.2	0.5	0.1	-0.2	8.5	11.4	13.1	-0.2	-1.0	-1.1
4/14/93	10.0	10.1	8.8	0.4	0.1	-0.3	8.6	11.5	12.9	0.1	-0.7	-0.9
4/16/93	9.6	9.6	8.5	0.5	0.2	-0.2	9.2	11.5	12.5	-0.3	-0.6	-0.8
4/18/93	9.3	9.3	8.1	0.4	0.0	-0.3	9.3	11.4	12.3	-0.3	-0.4	-0.7
4/20/93	9.3	9.3	8.3	0.5	0.3	0.0	9.3	11.3	12.2	0.0	-0.7	-0.8
4/22/93	8.8	8.8	7.8	0.3	0.1	-0.3	9.3	11.3	12.3	-0.4	-0.3	-0.6
4/24/93	8.6	8.5	7.7	-0.2	-0.3	-1.1	9.2	11.3	12.4	-0.3	-0.6	-0.8
4/26/93	8.4	8.5	7.8	0.0	-0.3	-2.0	9.2	11.2	12.3	-0.3	-0.7	-0.9
4/28/93	8.1	8.2	7.6	-0.3	-0.5	0.2	9.6	11.5	12.7	-0.4	-0.9	-1.0
4/30/93	8.2	8.3	7.9	-0.1	-0.2	0.4	9.4	11.3	12.8	-0.1	-0.6	-0.8
5/2/93	8.0	8.3	8.0	-0.2	-0.1	0.9	9.7	11.5	13.1	-0.2	-0.7	-0.9
5/4/93	7.9	8.2	8.1	0.7	0.9	2.3	9.4	11.5	13.3	-0.1	-0.6	-0.8
5/6/93	7.9	8.2	8.2	0.9	1.2	2.9				-0.2	0.2	-0.2
5/8/93	7.9	8.4	8.4	1.1	1.7	3.9				0.1	0.4	0.1
5/10/93	7.8	8.4	8.5	0.9	1.9	5.6				0.1	0.4	0.2
5/12/93	7.8	8.4	8.7	-0.1	1.5	4.5				0.0	0.2	0.2
5/14/93	7.3	8.0	8.4	0.9	2.0	5.7				-0.2	-0.5	-0.7
5/16/93	7.2	8.0	8.7	1.1	2.7	7.0	9.8	12.6	15.5	-0.2	-0.6	-0.6
5/18/93	7.2	8.1	8.9	1.8	3.6	8.8	9.8	12.7	15.7	0.2	-0.1	0.5

	Warm Water			Passive Warming			Heat Tape			Control		
Date	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	7.5'	4.5'	2.5'	5.25/ 7.5'	4.25/ 4.5'	2.0/ 2.5'
5/20/93	7.4	8.4	9.6	2.4	4.6	10.0	10.0	12.8	16.0	0.5	0.5	1.5
5/22/93	7.6	8.8	10.0	3.1	5.5	10.9				0.8	1.1	2.3
5/24/93	7.3	8.4	9.7	3.4	5.9	10.8	9.8	12.9	16.3	0.8	1.1	2.5
5/26/93	7.4	8.5	10.0	3.9	6.5	11.5				1.1	1.5	3.5
5/28/93	7.7	8.9	10.4	4.3	7.1	11.9				1.5	1.9	4.2
5/30/93	7.6	8.8	10.3	4.7	8.3	13.7				1.7	1.9	4.6
6/1/93	7.6	8.8	10.5	4.4	7.6	13.1				2.0	4.7	8.3
6/3/93	7.6	9.0	10.9	5.6	9.2	15.4				2.8	4.6	7.2
6/5/93	7.5	9.0	11.0	5.8	8.8	14.9				3.3	6.3	10.3
6/7/93	7.8	9.4	11.5	6.4	10.2	16.0				4.2	6.9	9.8
6/9/93	8.0	9.6	11.5	6.1	10.1	15.2				4.9	7.8	10.8
6/11/93	8.0	9.7	11.4	6.9	10.2	14.8				5.2	7.8	8.1
6/13/93	8.0	9.7	11.4	7.5	10.3	14.7				5.5	8.0	8.9
6/15/93	7.9	9.5	11.5	7.6	10.3	15.4				5.7	8.2	11.5
6/17/93	8.1	9.8	11.9	7.7	11.3	16.8				6.2	9.0	12.3
6/19/93	8.3	10.1	12.3	8.5	11.3	16.2				6.7	9.4	13.3
6/21/93	8.9	11.5	14.4	8.8	11.5	15.8				6.9	9.7	12.6
6/23/93	9.8	12.9	15.9	8.6	12.0	16.5				7.3	10.0	12.8
6/25/93	10.2	13.9	19.4	8.3	12.8	17.5					10.3	14.0
6/27/93	11.3	15.6	21.4								10.4	14.1
6/29/93	12.6	16.9	20.5	9.2	12.6	17.6						
7/1/93	13.4	18.1	21.7	9.3	12.7	18.0				8.8	10.9	14.6
7/3/93	14.6	19.4	22.9	10.1	13.0	18.5				9.3	11.2	14.9
7/5/93	15.0	19.5	22.6	10.6	13.3	18.7				9.6	11.8	14.9
7/7/93	14.9	19.1	21.7	10.1	13.8	19.0	12.5	16.8	21.1	9.9	12.2	14.8
7/9/93	15.1	19.0	21.0	11.5	14.0	17.9				10.4	11.7	15.4
7/11/93	14.7	18.3	20.3	10.6	14.3	18.7				10.6	12.3	14.7
7/13/93	14.0	17.3	19.5	10.6	14.2	18.9	13.1	17.3	21.7	10.2	11.9	15.5
7/15/93	13.8	17.0	19.3	10.8	14.3	19.4				10.3	12.3	15.7
7/17/93	13.7	16.9	19.4	10.9	14.7	19.9	13.3	17.7	22.1	10.7	12.8	15.9
7/19/93	13.6	16.6	19.1	11.3	14.9	20.0	13.5	17.9	22.3	11.0	12.9	15.7
7/21/93	13.4	16.4	18.6	11.2	14.8	19.9	13.6	18.0	22.3	11.1	13.0	16.0
7/23/93	13.3	16.1	18.5	11.4	15.0	20.2	13.5	17.9	22.3	11.5	12.9	16.0
7/25/93	13.4	16.1	18.1	11.5	15.2	20.3	13.5	17.9	22.3	11.3	13.1	16.4
7/27/93	13.2	15.9	18.1	13.0	15.6	20.1	13.5	17.8	22.0	11.4	13.1	16.4
7/29/93	12.4	15.8	18.0	13.0	15.7	20.3	13.7	17.9	22.3	11.5	14.3	16.6
7/31/93	12.9	15.4	17.8	14.1	15.7	20.0	13.5	17.8	22.2	11.6	14.4	16.5
8/2/93	12.8	15.4	17.6	13.2	15.6	19.8				11.6	14.2	16.2
8/4/93	12.7	15.1	17.2	12.3	15.9	20.2				11.8	14.3	16.1
8/6/93	12.4	14.9	16.5	18.3	13.2	15.4				11.6	13.8	16.7
8/8/93	12.4	14.6	15.7	17.8	13.4	15.3				11.6	13.7	14.8
8/10/93	12.1	14.1	15.1	17.7	13.3	15.0	13.9	18.3	22.7	11.4	13.3	14.3
8/12/93	12.1	14.0	15.0	14.7	14.9	17.4				11.3	13.1	14.3
8/14/93	12.0	13.8	14.8	17.5	13.1	14.8				11.2	13.4	15.6
8/16/93	12.0	13.6	14.5	17.5	13.0	14.7				12.0	12.9	13.9

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Date	Warm Water			Passive Warming			Heat Tape			Control		
	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	7.5'	4.5'	2.5'	5.25/ 7.5'	4.25/ 4.5'	2.0/ 2.5'
8/18/93	11.8	13.3	14.1	17.3	13.0	14.6	14.0	18.5	22.9	10.1	12.6	13.6
8/20/93	11.7	13.1	13.6	14.3	14.7	17.0				10.1	12.4	13.2
8/22/93	11.5	12.9	13.5	14.5	14.4	16.1				10.7	12.8	14.8
8/24/93	11.3	12.7	13.5	14.3	14.3	15.8				10.3	12.5	14.4
8/26/93	11.1	12.5	12.2	13.5	14.1	15.0	14.2	18.5	22.9	10.6	12.1	12.8
8/28/93	10.9	11.9	11.8	13.4	13.5	14.8	14.4	18.4	21.9	11.3	11.5	12.2
8/30/93	10.7	11.7	11.6	13.1	13.5	14.8	14.4	18.4	21.9	11.7	11.2	11.9
9/1/93	10.5	11.5	11.8	11.6	13.9	14.7	14.5	18.2	21.3	10.9	11.1	12.2
9/3/93	10.1	11.1	11.7		14.1	13.6	14.5	18.4	22.3	10.4	11.2	12.4
9/5/93	10.0	11.0	11.7		13.6		14.6	18.1	21.1	9.8	10.9	11.9
9/7/93	10.0	11.1	11.5		13.5		14.9	18.4	21.2	9.7	11.1	12.0
9/9/93	9.9	11.0	11.6	11.1	13.3	15.1	14.8	18.2	21.1	9.6	11.2	12.8
9/11/93	10.0	11.1	11.4	11.4	12.8	14.0	14.6	18.6	21.5	9.9	11.1	13.0
9/13/93	9.9	10.9	10.9	11.2	12.6	13.5	15.1	18.5	21.3	9.8	11.0	12.6
9/15/93	9.7	10.4	10.0	11.2	12.3	13.1	15.2	18.4	21.2	9.8	10.9	12.3
9/17/93	9.6	10.4	10.2	11.0	12.1	12.9	15.3	18.5	21.3	9.8	10.7	11.8
9/19/93	9.5	10.3	10.3	10.9	11.9	12.1	15.2	18.5	20.8	9.7	10.6	11.3
9/21/93	9.3	10.0	8.6	10.7	11.4	11.0	15.3	18.4	20.3	9.6	10.1	10.3
9/23/93	9.1	9.3	7.5	10.5	10.5	10.0	15.2	18.2	20.5	9.2	9.3	9.6
9/25/93	8.8	8.7	6.9	10.2	10.2	9.6	15.3	18.1	19.9	9.1	9.2	9.1
9/27/93	8.5	8.2	5.7	10.0	9.7	8.9	15.2	18.0	19.6	8.9	8.8	9.0
9/29/93	8.2	7.9	4.9	9.8	9.5	8.2	15.1	17.7	19.4	8.5	8.2	7.5
10/1/93	7.8	7.1	4.3	9.5	8.9	7.8	15.0	17.6	19.0	8.3	7.5	6.3
10/3/93	7.5	6.6	3.8	9.1	8.5	7.4	14.9	17.3	18.9	7.8	6.8	4.8
10/5/93	7.1	6.1	4.0	8.9	8.3	7.4	14.8	17.2	18.9	7.4	6.6	6.6
10/7/93	6.8	5.9	3.6	8.7	7.9	7.2	14.6	16.9	18.7	7.2	6.0	5.7
10/9/93	6.4	5.4	3.1	8.5	7.8	7.1				6.7	6.0	5.5
10/11/93	6.7	5.5	4.6	8.2	7.6	7.2	14.5	16.8	18.9	6.4	5.6	6.7
10/13/93	5.9	5.3	3.7	8.0	7.2	6.9	14.5	16.8	18.8	6.1	5.5	4.8
10/15/93	5.8	5.0	3.5	7.8	7.2	6.7	14.4	16.7	18.7	5.9	5.3	4.6
10/17/93	5.6	4.5	3.4	7.7	6.8	6.5	14.3	16.6	18.6	5.8	5.2	4.3
10/19/93	5.5	5.0	2.7	7.6	6.8	6.4	14.3	16.6	18.5	5.6	4.8	5.9
10/21/93	5.4	4.6	2.3	7.5	6.8	5.9	14.3	16.5	18.3	5.4	4.7	6.0
10/23/93	5.2	4.2	2.0	7.3	6.3	5.4	14.1	16.3	17.9	5.1	4.4	6.1
10/25/93	4.9	4.0	1.6	7.1	6.1	4.8	14.0	16.1	17.6	4.8	4.1	5.8
10/27/93	4.8	3.7	1.4	6.9	5.8	4.5	14.0	16.0	17.4	4.6	3.8	5.1
10/29/93	4.5	3.0	1.2	6.7	5.4	4.3	13.9	15.9	17.2	4.4	3.6	5.6
10/31/93	4.4	3.0	1.1	6.5	5.4	4.1	13.8	15.7	17.2	4.3	3.4	4.9
11/2/93	4.2	3.1	1.0	6.3	5.0	4.0	13.7	15.6	17.2	4.0	3.4	4.8
11/4/93	4.0	3.0	0.9	6.1	4.8	3.8	13.6	15.6	17.2	3.9	3.2	4.0
11/6/93	3.9	2.7	0.8	6.0	4.7	3.5	13.5	15.5	17.0	3.7	3.0	4.1
11/8/93	3.7	2.7	0.7	5.8	4.5	3.3	13.4	15.4	16.9	3.5	2.9	4.0
11/10/93	3.5	2.3	0.6	5.6	4.3	3.1	13.3	15.2	16.8	3.5	2.8	4.5
11/12/93	3.4	1.7	0.5	5.5	4.1	3.1	13.2	15.1	16.7	3.4	2.6	4.0
11/14/93	3.3	1.8	0.5	5.3	4.1	3.1	13.2	15.1	16.6	3.2	2.5	4.5

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	Warm Water			Passive Warming			Heat Tape			Control		
Date	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	7.5'	4.5'	2.5'	5.25/ 7.5'	4.25/ 4.5'	2.0/ 2.5'
11/16/93	3.3	2.0	0.5	5.2	4.1	3.1	13.1	15.0	16.6	3.1	2.4	5.1
11/18/93	3.2	2.3	0.5	5.3	4.0	3.1	13.1	15.2	16.7	3.1	2.2	4.9
11/20/93	3.2	2.3	0.4	5.1	3.8	2.8	13.1	15.2	16.4	2.9	2.2	4.4
11/22/93	2.8	1.8	0.0	4.8	3.7	2.4	12.8	14.7	15.7	2.7	2.1	4.2
11/24/93	2.7	1.1	-0.1	4.7	3.5	2.2	12.8	14.6	15.5	2.6	2.0	4.6
11/26/93	2.8	1.5	0.0	4.6	3.3	2.2	12.9	14.5	15.6	2.6	1.8	3.8
11/28/93	2.6	0.8	-0.1	4.6	3.2	2.0	12.7	14.4	15.5	2.5	1.7	3.9
11/30/93	2.7	2.1·	-0.1	4.4	3.2	1.9	12.8	14.5	15.6	2.5	1.7	4.0
12/2/93	2.4	1.0	-0.3	4.2	3.0	1.7	12.5	14.2	15.3	2.3	1.6	3.5
12/4/93	2.0	0.8	-0.3	4.1	2.8	1.7	12.5	14.2	15.3	2.2	1.6	3.6
12/6/93	1.9	0.3	-0.4	4.0	2.7	1.5	12.3	14.1	15.2	2.0	1.3	3.8
12/8/93	1.8	0.1	-0.3	3.9	2.7	1.5	12.3	14.0	15.3	2.1	1.4	3.3
12/10/93	1.8	1.4	-0.3	3.8	2.5	1.5	12.4	14.0	15.3	2.0	1.3	3.2
12/12/93	1.7	0.9	-0.4	3.7	2.5	1.4	12.2	13.9	15.2	1.9	1.3	3.3
12/14/93	1.7	0.9	-0.4	3.6	2.5	1.3	12.2	13.9	15.1	1.9	1.2	3.2
12/16/93	1.7	1.5	-0.4	3.5	2.3	1.3	12.1	13.9	15.0	1.8	1.2	2.7
12/18/93	1.5	1.2	-0.5	3.4	2.3	1.1	11.9	13.8	14.8	1.7	1.0	3.0
12/20/93	1.4	0.6	-0.5	3.3	2.1	1.1	11.9	13.7	14.8	1.7	0.9	3.4
12/22/93	1.4	0.6	-0.7	3.2	2.1	1.1	11.9	13.7	14.8	1.5	0.9	3.6
12/24/93	1.3	0.8	-0.7	3.1	2.0	0.9	11.8	13.6	14.7	1.4	0.7	3.4
12/26/93	1.3	0.8	-0.7	3.1	2.0	0.9	11.7	13.5	14.5	1.3	0.8	2.6
12/28/93	1.2	0.6	-1.0	2.9	1.9	0.9	11.7	13.3	14.1	1.3	0.7	1.6
12/30/93	1.0	0.7	-1.1	2.9	1.8	0.8	11.5	13.2	13.9	1.1	0.6	3.1
1/1/94	1.0	1.0	-1.0	2.8	1.8	0.7	11.5	13.0	13.8	1.1	0.5	3.5
1/3/94	1.1	1.4	-1.4	2.9	1.9	0.9	11.5	13.0	13.5	1.1	0.6	3.9
1/5/94	1.2	1.2	-2.0	2.9	2.0	0.8	11.5	13.0	13.3	1.1	0.4	4.4
1/7/94	0.9	1.0	-3.0	2.8	1.8	0.7	11.6	12.9	13.0	0.9	0.2	3.3
1/9/94	0.9	0.7	-3.8	2.8	1.8	0.6	11.4	12.7	12.4	0.8	0.3	2.4
1/11/94	0.7	0.8	-3.8	2.6	1.5	0.4	11.3	12.5	12.0	0.6	0.1	1.1
1/13/94	0.6	0.5	-4.0	2.5	1.5	0.3	11.1	12.2	11.4	0.4	-0.3	1.2
1/15/94	0.6	0.3	-4.4	2.4	1.4	0.2	11.1	11.9	11.3	0.4	-0.3	0.1
1/17/94	0.6	0.3	-3.0	2.3	1.4	0.2	10.9	11.7	11.1	0.4	-0.3	0.6
1/19/94	0.5	-0.2	-2.8	2.3	1.3	0.2	10.8	11.6	11.1	0.4	-0.4	0.9
1/21/94	0.5	0.2	-2.6	2.2	1.2	0.1	10.5	11.3	11.3	0.3	-0.5	1.2
1/23/94	0.3	0.0	-2.4	2.2	1.2	0.1	10.4	11.3	11.6	0.3	-0.4	1.3
1/25/94	0.4	0.1	-2.5	2.1	1.1	0.1	10.2	11.3	11.9	0.1	-0.7	1.9
1/27/94	0.3	0.0	-2.4	2.1	1.1	0.1	10.5	11.4	12.3	0.1	-0.5	1.4
1/29/94	0.3	0.5	-2.5	2.0	1.1	0.1	10.3	11.4	12.3	0.1	-0.6	1.3
1/31/94	0.2	0.3	-2.1	2.0	1.0	0.1	10.3	11.4	12.4	0.1	-0.5	1.3·
2/2/94	0.2	0.7	-2.2	1.9	1.0	0.0	10.2	11.4	12.5	0.1	-0.5	1.3
2/4/94	0.2	0.6	-1.8	1.9	0.9	0.0	10.2	11.5	12.5	0.0	-0.7	1.5
2/6/94	0.2	0.3	-2.2	1.9	0.9	0.0	10.3	11.7	12.8	-0.1	-0.6	1.8
2/8/94	0.1	-0.2	-1.6	1.8	0.9	0.0	10.2	11.6	12.8	-0.1	-0.6	1.1
2/10/94	0.2	0.1	-2.3	1.8	0.9	0.0	10.0	11.6	12.7	0.0	-0.8	1.3
2/12/94	0.3	-0.1	-1.9	1.9	1.0	0.0	10.2	11.7	12.8	-0.1	-0.7	1.8

	Warm Water			Passive Warming			Heat Tape			Control		
Date	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	7.5'	4.5'	2.5'	5.25/ 7.5'	4.25/ 4.5'	2.0/ 2.5'
2/14/94	0.2	0.1	-2.4	1.8	0.9	0.0	10.3	11.9	13.0	-0.1	-0.7	1.4
2/16/94	0.2	0.1	-2.9	1.8	0.9	-0.1	10.3	11.9	12.6	-0.2	-0.9	0.9
2/18/94	0.0	-0.1	-3.4	1.7	0.8	-0.2	10.3	11.8	12.3	-0.2	-1.2	0.6
2/20/94	-0.1	-0.2	-3.7	1.7	0.8	-0.3	9.8	11.5	11.9	-0.3	-1.3	0.1
2/22/94	-0.1	-0.4	-3.9	1.6	0.7	-0.3	10.0	11.4	11.5	-0.3	-1.4	-0.1
2/24/94	-0.1	-0.3	-4.1	1.6	0.8	-0.4	10.0	11.2	11.2	-0.4	-1.5	-0.2
2/26/94	-0.2	-0.5	-4.3	1.5	0.6	-0.5	10.0	11.2	10.8	-0.5	-1.6	-0.5
2/28/94	-0.3	-0.8	-4.2	1.5	0.6	-0.5	9.9	10.9	10.5	-0.4	-1.6	-0.6
3/2/94	-0.2	-0.6	-3.8	1.5	0.7	-0.4	9.8	10.7	10.3	-0.4	-1.3	-0.2
3/4/94	-0.3	-0.5	-3.5	1.5	0.6	-0.4	9.7	10.6	10.3	-0.4	-1.4	0.1
3/6/94	-0.3	-0.4	-3.6	1.4	0.5	-0.5	9.7	10.5	10.4	-0.5	-1.4	-0.1
3/8/94	-0.4	-0.1	-3.8	1.3	0.5	-0.5	9.4	10.4	10.4	-0.5	-1.4	-0.2
3/10/94	-0.4	-0.1	-3.5	1.3	0.5	-0.5	9.3	10.3	10.6	-0.5	-1.3	-0.7
3/12/94	-0.4	-0.2	-3.3	1.3	0.5	-0.4	9.3	10.3	10.9	-0.5	-1.2	-0.7
3/14/94	-0.4	-0.6	-3.0	1.3	0.5	-0.4	9.3	10.3	11.2	-0.6	-1.2	-0.4
3/16/94	-0.4	-0.5	-2.9	1.3	0.5	-0.4	9.3	10.4	11.4	-0.6	-1.3	0.0
3/18/94	-0.5	-0.5	-3.3	1.2	0.5	-0.4	9.3	10.6	11.6	-0.6	-1.3	-0.2
3/20/94	-0.5	-0.7	-3.1	1.3	0.5	-0.5	9.3	10.7	11.5	-0.6	-1.3	-0.4
3/22/94	-0.5	-1.1	-3.8	1.1	0.4	-0.6	9.3	10.6	11.4	-0.7	-1.4	-1.2
3/24/94	-0.5	-1.5	-3.2	1.1	0.4	-0.5	9.1	10.4	11.1	-0.5	-1.1	-0.9
3/26/94	-0.6	-1.3	-2.7	1.1	0.3	-0.4	8.6	10.4	11.3	-0.6	-1.2	-0.3
3/28/94	-0.5	-3.1	-2.4	1.1	0.3	-0.4	8.9	10.5	11.6	-0.6	-1.0	-1.9
3/30/94	-0.5	-2.1	-2.1	1.1	0.3	-0.4	8.9	10.5	11.9	-0.5	-1.0	-1.5
4/1/94	-0.7	-1.7	-1.7	1.0	0.3	-0.4	8.9	10.5	12.2	-0.6	-0.9	-1.3
4/3/94	-0.7	-1.5	-1.5	1.0	0.3	-0.3	9.0	10.8	12.3	-0.6	-1.1	-1.2
4/5/94	-0.7	-1.0	-1.3	0.9	0.1	-0.3	9.0	11.1	12.2	-0.6	-1.2	-1.2
4/7/94	-0.7	-0.8	-1.4	0.9	0.1	-0.7	9.3	11.1	11.9	-0.7	-1.1	-1.1
4/9/94	-0.6	-0.8	-1.3	0.9	0.0	-0.7	9.3	11.1	11.7	-0.7	-1.0	-1.1
4/11/94	-0.6	-0.8	-1.2	0.9	0.1	-0.7	9.4	11.0	11.6	-0.7	-1.0	-1.1
4/13/94	-0.7	-0.7	-1.5	0.9	0.1	-0.7	9.4	11.0	11.6	-0.7	-1.0	-1.2
4/15/94	-0.6	-0.8	-1.9	0.8	0.0	-0.7	9.4	10.9	11.7	-0.8	-1.2	-1.5
4/17/94	-0.7	-1.2	-2.2	0.8	-0.1	-0.7	9.4	11.0	11.8	-0.6	-1.2	-1.9
4/19/94	-0.7	-2.1	-1.7	1.0	0.1	-0.7	9.3	10.8	11.8	-0.6	-1.1	-1.5
4/21/94	-0.7	-1.2	-1.3	1.1	0.2	-0.7	9.2	10.8	11.9	-0.6	-0.9	-1.2
4/23/94	-0.8	-1.3	-1.2	1.2	0.4	-0.6	9.3	11.0	12.1	-0.4	-0.6	-0.9
4/25/94	-0.8	-1.2	-1.2	0.8	0.3	-0.6	9.3	11.0	12.3	-0.5	-0.7	-0.9
4/27/94	-0.8	-0.9	-1.1	0.9	0.5	-0.4	9.2	11.1	12.8	-0.5	-0.6	-0.7
4/29/94	-0.8	-1.0	-1.0	0.9	0.6	-0.2	9.2	11.1	13.4	-0.4	-0.6	-0.7
5/1/94	-0.8	-1.2	-1.0	1.0	0.8	0.0	9.2	11.4	13.8	-0.4	-0.5	-0.6
5/3/94	-0.8	-1.1	-0.9	1.1	0.9	0.0	9.2	11.5	14.2	-0.6	-0.6	-0.7
5/5/94	-0.8	-0.5	-0.5	1.3	1.0	0.6	9.2	11.7	14.5	-0.3	-0.4	-0.3
5/7/94	-0.7	-0.3	-0.3	1.5	1.2	1.1	9.3	11.9	14.9	-0.3	-0.5	-0.3
5/9/94	-0.8	-0.2	-0.1	1.6	1.2	2.3	9.3	12.1	15.2	-0.3	-0.4	-0.3
5/11/94	-0.8	0.6	0.2	1.8	1.6	3.7	9.4	12.2	15.5	0.0	-0.6	-0.4
5/13/94	-0.8	-0.5	0.8	2.1	2.4	5.6	9.4	12.4	15.9	-0.2	-0.6	-0.3

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	Warm Water			Passive Warming			Heat Tape			Control		
Date	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	5.25/ 7.0'	4.0/ 4.25'	2.0/ 2.5'	7.5'	4.5'	2.5'	5.25/ 7.5'	4.25/ 4.5'	2.0/ 2.5'
5/15/94	-0.8	-0.7	1.2	2.4	3.2	7.7	9.5	12.5	16.1	-0.2	-0.3	0.4
5/17/94	-0.8	-0.9	1.3	2.8	4.4	8.9	9.6	12.8	16.4	-0.3	-0.4	0.6
5/19/94	-0.9	-0.1	1.7	3.3	5.2	9.9	9.6	12.9	16.7	-0.3	-0.5	0.9
5/21/94	-0.8	-1.4	2.3	3.8	6.0	11.0	9.9	13.2	17.0	-0.3	-0.3	1.3
5/23/94	-0.6	-0.7	2.4	4.3	6.8	11.6	9.9	13.4	17.4	-0.3	-0.3	1.7
5/25/94	-0.6	-0.6	3.0	4.7	7.4	12.2	10.0	13.6	17.6	-0.4	-0.4	2.0
5/27/94	-0.4	-0.5	3.3	5.2	7.9	12.9	10.1	13.7	17.7	-0.2	-0.2	2.3
5/29/94	-0.1	-1.3	3.5	5.5	8.5	13.3	10.2	13.9	17.9	-0.4	-0.2	2.5
5/31/94	0.0	-1.9	3.9	5.9	8.8	13.5	10.4	14.1	18.2	-0.2	-0.1	2.9
6/2/94	0.2	-1.1	4.5	6.3	9.2	14.0	10.4	14.1	18.2	-0.1	0.2	3.3
6/4/94	0.2	1.0	5.4	6.5	9.6	14.7	10.5	14.2	18.4	-1.1	-0.1	3.5
6/6/94	0.7	0.7	5.5	7.0	10.3	14.9	10.6	14.2	18.6	-0.3	0.6	4.2
6/8/94	0.9	0.9	6.3	7.3	10.5	15.3	10.6	14.6	18.8	0.3	1.1	4.8
6/10/94	0.9	1.0	7.2	7.4	10.8	16.2	10.7	14.8	18.9	0.6	1.1	5.4
6/12/94	1.4	1.2	8.0	7.7	11.2	17.1	10.9	14.8	19.1	1.1	1.4	6.2
6/14/94	1.9	1.6	9.1	8.0	11.9	18.1	10.9	14.8	19.3	1.3	1.9	6.9
6/16/94	2.5	3.1	8.7	8.5	12.6	17.5	11.1	15.1	19.7	1.9	2.8	7.3
6/18/94	3.1	4.1	8.0	8.9	12.8	16.1	11.2	15.1	19.9	2.7	3.8	7.4
6/20/94	3.4	4.6	8.5	9.2	12.6	15.3	11.4	15.3	19.9	3.4	4.5	7.7
6/22/94	3.6	5.1	7.5	9.4	12.3	15.4	11.5	15.6	19.8	3.8	5.3	8.5
6/24/94	4.0	5.6	8.2	9.5	12.5	15.5	11.5	15.6	19.7	4.4	5.8	9.1
6/26/94	4.4	6.1	7.1	9.7	12.5	15.5	11.8	15.8	19.9	4.9	6.3	9.3
6/28/94	4.5	6.4	4.6	9.6	12.4	16.0	11.8	15.7	19.8	5.4	7.1	10.0
6/30/94	4.6	6.8	3.6	9.6	12.5	17.2	11.9	15.7	19.9	5.8	7.5	10.6
7/2/94	5.2	7.3	8.2	9.9	13.2	18.5	11.9	15.7	20.0	7.6	7.6	11.3
7/4/94	5.6	7.8	8.9	10.2	13.7	18.4	12.1	15.9	20.5	6.8	8.4	11.8
7/6/94	5.9	8.3	3.9	10.4	13.9	18.1	12.2	16.2	20.6	7.2	8.9	11.9
7/8/94	6.2	8.5	5.5	10.5	13.8	17.5	12.3	16.3	20.7	7.5	9.1	12.2
7/10/94	6.4	8.9	6.3	10.5	14.7	17.2	12.3	16.3	20.8	7.8	9.5	12.6

APPENDIX B: Sample Linear Regression Calculations

The following data file was constructed from the original data printed in the project report.

Soil gas probes for the following plots are indicated by

Warm Water	A#_
Passive Warming	P#_
Control	C#_
Heat Tape	H#_
Background	B#_
Perimeter	PE#_ & PP#_

Soil gas measurements are in units of %O2

In Situ Respiration Test #1 (1 - 7 Oct 1991)

Time (hrs)	A1B	A2C	A5B	A6A	A6B	Time (hrs)	A2B	Time (hrs)	A3C	Time (hrs)	A6C
0	8.0	15.0	14.0	12.0	8.4	0	19.0	0	17.0	0	4.4
4	6.2	14.0	9.1	11.0	7.6	4	15.0	4	16.0	14	4.0
9	1.8	12.0	8.0	10.0	7.0	9	11.0	9	14.0	25	3.8
14		9.0	8.0	8.0	6.0	14	7.3	25	13.0	33	
25		8.2	5.9	6.9	4.5	33	4.5	33	13.0	49	
33		7.5	3.9	4.5		70	4.4	49	13.0	70	
49		9.9		3.1				70	13.0	96	
70		7.9		2.2				96	13.0	146	
96		0.8						146	12.0		
Intercept	8.35	13.09	11.61	10.93	8.31		14.00		14.95		4.38
Slope	-0.697	-0.112	-0.244	-0.146	-0.155		-0.176		-0.024		-0.024
Rsquare	0.970	0.755	0.822	0.917	0.995		0.608		0.521		0.985

Time (hrs)	A3A	Time (hrs)	PE4A	PE4B	PE5A	PE6B	PE6C	PE7A	Time (hrs)	PE6A
0	20.0	0	20.9	20.9	19.8	18.5	13.5	16.0	4	18.3
4	17.0	4	20.9	20.9	20.9	19.0	12.2	15.2	9	18.0
9	15.0	9	20.6	19.8	20.0	18.8	12.0	14.5	14	18.0
70	11.0	14	20.7	19.9	20.5	18.8	12.8	14.4	25	17.6
146	9.8	25	20.8	19.5	19.8	18.0	12.0	13.5	33	16.8
		33	20.5	18.7	19.5	17.5	12.0	12.0	49	15.8
Intercept	17.25	49	19.9	18.3	19.7	17.8	12.6	11.8	70	15.0
Slope	-0.059	70	19.0	17.6	18.7	15.5	11.7	8.7	96	13.9
Rsquare	0.770	96	18.6	17.6	18.0	14.1	11.3	7.1	146	11.6
		146	17.5	16.2	16.8	12.1	11.0	7.1		
		Intercept	21.04	20.32	20.48	19.19	12.65	15.01		18.49
		Slope	-0.025	-0.031	-0.025	-0.049	-0.012	-0.067		-0.048
		Rsquare	0.968	0.904	0.913	0.963	0.617	0.897		0.993

Time (hrs)	P1A	P1B	P1C	P2A	P2B	P2C	P3A	P3B	P3C	P4A	P4B
0	20.9	20.9	20.9	20.9	20.7	20.8	20.9	20.9	20.9	20.7	20.7
4	20.2	20.5	20.0	20.6	20.0	20.2	20.5	20.7	20.5	20.8	20.6
9	20.2	20.5	20.0	20.7	20.0	20.3	20.6	20.6	20.5	20.8	20.5
14	19.8	20.0	20.0	21.3	19.5	20.0	20.0	20.3	20.4	20.2	20.0
25	19.3	19.5	19.5	20.1	19.2	19.7	20.0	20.0	20.2	20.0	19.7
33	18.5	18.8	18.9	19.5	18.5	19.0	20.3	19.3	19.5	19.2	18.8
49	17.5	18.0	18.4	19.2	17.8	18.6	18.8	18.9	19.4	18.4	18.0
70	16.0	16.7	17.8	18.9	17.0	18.0	17.9	18.1	19.1	17.5	16.8
96	15.0	15.8	17.4	18.5	17.0	18.0	17.2	17.5	18.8	16.9	15.8
146	13.9	15.5	16.5	16.9	14.7		17.5	16.0	18.5	15.0	13.5
Intercept	20.38	20.45	20.21	20.89	20.14	20.41	20.58	20.75	20.51	20.80	20.72
Slope	-0.050	-0.041	-0.029	-0.027	-0.038	-0.030	-0.027	-0.034	-0.016	-0.041	-0.051
Rsquare	0.955	0.916	0.931	0.932	0.959	0.907	0.840	0.986	0.878	0.981	0.992

Time (hrs)	P4C	P5A	P5B	P5C	P6A	P6B	P6C
0	20.7	20.7	20.7	20.7	20.9	20.5	20.5
4	20.2	20.7	20.5	20.1	20.5	20.0	20.0
9	20.3	20.7	20.3	20.0	20.4	19.6	19.7
14	20.1	20.1	20.0	19.9	19.2	19.0	19.3
25	19.5	20.1	19.2	19.3	20.0	18.1	19.7
33	18.8	19.5	18.3	18.4	19.3	17.0	17.8
49	18.1	19.0	17.5	17.9	18.9	15.6	17.0
70	17.1	18.0	16.7	16.0	18.2	14.0	15.8
96	16.4	17.0	15.0	16.0	17.2	12.4	14.6
146	15.0	15.2	12.5	14.1	15.8	10.2	12.8
Intercept	20.42	20.84	20.62	20.28	20.52	19.91	20.15
Slope	-0.040	-0.039	-0.057	-0.046	-0.033	-0.073	-0.054
Rsquare	0.973	0.994	0.993	0.957	0.954	0.971	0.963

Time (hrs)	C1A	C1B	C2A	C3A	C4A	C4B	C5A	C6A	Time (hrs)	C2B
0	16.5	12.8	19.5	20.9	20.2	8.7	20.5	19.5	0	17.0
4	15.8	11.8	18.4	20.2	20.3	10.5	19.9	19.3	4	13.2
9	15.0	11.0	18.3	20.0	20.0	9.2	20.3	18.6	9	13.4
14	14.0	11.5	18.0	20.2	20.0	7.8	18.6	17.8	14	12.5
25	12.9	10.5	17.5	20.0	19.0	8.5	17.4	16.0	33	13.2
33	11.9	9.5	17.1	19.6	18.7	7.6	16.6	14.8	49	11.1
49	9.5	6.9	16.0	19.0	17.4	6.1	14.8	12.5	70	11.3
70	7.1	5.4	14.4	18.6	16.1	5.0	12.9	9.9	146	9
96	6.1	5.5	13.0	17.9	15.1	4.3	10.3	7.6		
146	2.5	2.2	9.1	15.0	11.0		6.1	3.9		
Intercept	15.47	11.92	19.11	20.72	20.60	9.47	20.23	19.03		14.18
Slope	-0.097	-0.072	-0.067	-0.035	-0.063	-0.058	-0.101	-0.113		-0.039
Rsquare	0.963	0.940	0.993	0.956	0.991	0.884	0.990	0.976		0.685

In Situ Respiration Test #2 (10 - 14 Nov 1991)

Time (hrs)	P4C	P6A	P6B	Time (hrs)	P4A	P4B	P6C
0	20.9	20.9	20.9	0	20.9	20.9	20.1
3	20.4	20.9	20.9	24	19.9	19.5	19.9
24	19.9	19.2	19.5	48	19.0	18.6	18.8
48	19.0	18.7	17.8				
Intercept	20.72	20.85	21.01		20.88	20.82	20.25
Slope	-0.036	-0.049	-0.066		-0.040	-0.048	-0.027
Rsquare	0.960	0.922	0.996		0.999	0.984	0.862

Time (hrs)	C1A	C1B	C1C	C6A	Time (hrs)	C6B	Time (hrs)	PE1A	Time (hrs)	PE1B
0	17.3	10.1	6.3	20.5	0	11.0	3	20.9	3	20.9
3	18.3	12.9	5.6	19.7	24	8.5	24	20.5	24	20.9
24	14.5	6.5	4.5	18.0	48	5.0	48	20.9	96	20.5
48	14.0	7.4	3.9	16.2			96			
96		4.9								
							Intercept	20.76		20.99
Intercept	17.63	10.60	5.94	20.20		11.17	Slope	0.00		-0.01
Slope	-0.086	-0.065	-0.046	-0.085		-0.125	Rsquare	0.001		0.783
Rsquare	0.822	0.669	0.911	0.983		0.991				

In Situ Respiration Test #3 (7 - 14 Dec 1991)

Time (hrs)	A1B	A6C	Time (hrs)	P4A	P4B	P4C	P6A	P6B	P6C
0	5.9	5.1	0	20.9	20.7	20.7	20.4	20.1	20.1
4	5.6	5.4	4	20.9	20.5	20.5	20.1	20.1	20.1
8	4.7	5.8	8	20.0	20.0	20.0	20.5	19.8	19.8
22		2.2	22	20.2	19.6	20.6	19.5	19.4	19.8
47			47	18.8	18.2	19.1	18.9	18.0	18.8
98			98	17.1	17.2	18.6	17.1	17.0	17.4
169			169	15.5	14.2	16.9	15.0		16.9
Intercept	6.00	5.89	Intercept	20.67	20.46	20.56	20.39	20.06	20.01
Slope	-0.150	-0.149	Slope	-0.032	-0.037	-0.022	-0.032	-0.033	-0.021
Rsquare	0.923	0.750	Rsquare	0.969	0.984	0.943	0.991	0.961	0.940

Time (hrs)	C1A	Time (hrs)	C1B	Time (hrs)	C6A	Time (hrs)	C6B
0	16.2	0	12.0	0	20.0	0	12.0
8	16.3	4	10.0	4	16.9	4	9.9
22	15.6	8	9.0	8	20.0	8	9.8
47	13.2	47	6.8	22	18.5	22	8.1
98	12.1	98	7.2	47	16.8	47	7.7
169	8.8			98	14.2		
				169	11.3		
Intercept	16.26		10.24		19.18		10.74
Slope	-0.045		-0.040		-0.048		-0.076
Rsquare	0.971		0.604		0.888		0.726

In Situ Respiration Test #4 (28 Jan - 2 Feb 1992)

Time (hrs)	A1B	Time (hrs)	A1C	A2B	A2C	A3B	A3C	A4B	A5C	A6A
0	8.9	0	13.5	18.4	15.0	17.5	21.5	4.3	12.1	5.2
5	6.0	5	12.8	15.2	13.2	17.0	16.2	2.5	10.0	4.0
54	1.0	31	12.5	9.4	10.5	13.8	14.0	1.5	9.5	3.8
		54	12.0	4.8	10.0	12.5	13.8	1.0	9.3	3.0
Intercept	7.83		13.22	17.33	14.14	17.36	18.93	3.48	11.11	4.72
Slope	-0.128		-0.023	-0.239	-0.088	-0.096	-0.114	-0.051	-0.039	-0.032
Rsquare	0.920		0.854	0.978	0.868	0.973	0.630	0.775	0.583	0.779

Time (hrs)	A4C	Time (hrs)	P1A	P1B	P1C	P2A	P2B	P2C	P3A	P3B	P3C
0	8.9	0	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9
31	8.5	6	20.5	20.8	20.5	20.8	20.7	20.8	20.8	20.8	20.9
54	8.0	30	19.8	20.0	19.9	20.0	20.0	20.1	19.9	19.9	20.2
		53	19.1	19.5	19.5	19.6	19.5	19.9	19.1	19.1	19.9
		104	17.6	18.7	18.8	18.1	18.1	19.0	18.8	18.1	18.4
Intercept	8.93	292	13.6	14.3	15.8		14.8	16.0	13.3	13.9	16.6
Slope	-0.016										
Rsquare	0.978		20.56	20.84	20.57	20.92	20.67	20.79	20.86	20.70	20.69
			-0.024	-0.022	-0.017	-0.027	-0.021	-0.017	-0.025	-0.024	-0.015
			0.990	0.997	0.989	0.995	0.989	0.996	0.986	0.992	0.947

Time (hrs)	P4A	P4B	P4C	P5A	P5B	P5C	P6A	P6C	Time (hrs)	P6B
0	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9	0	20.9
6	20.9	20.8	20.9	20.5	20.7	20.7	20.6	20.8	6	20.9
30	20.0	19.6	20.0	20.1	19.7	20.1	19.9	20.0	30	19.5
53	19.2	18.4	19.5	19.5	18.6	19.7	19.1	18.7	104	17.8
104	18.0	17.2	18.9	18.1	17.2	18.9	17.9	18.6	292	13.1
292	13.7	11.9	15.1	13.6	13.0	14.2	13.9	14.5		
Intercept	20.78	20.59	20.80	20.78	20.50	20.91	20.62	20.64		21.39
Slope	-0.025	-0.030	-0.020	-0.025	-0.027	-0.023	-0.023	-0.021		-0.076
Rsquare	0.994	0.988	0.992	0.999	0.980	0.995	0.992	0.970		0.983

Time (hrs)	C1A	C1B	C2A	C3A	C3B	C4B	C5C	C6A	Time (hrs)	C4A
0	19.3	15.0	20.9	20.9	15.5	10.1	14.0	20.5	7	20.8
7	19.0	13.7	20.5	20.9	14.5	8.0	13.0	20.2	29	20.5
29	17.5	12.0	19.5	20.5	10.8	6.2	13.0	18.8	51	18.9
51	15.9	10.2	18.0	19.0	9.5	5.3	11.4	17.8	104	18.3
104	14.5	9.5	17.0	19.3				15.5	293	11.8
293	8.0	2.2	12.1	16.4				9.8		
Intercept	18.73	13.67	20.34	20.71	15.23	9.27	13.78	20.00		21.31
Slope	-0.038	-0.040	-0.029	-0.015	-0.122	-0.086	-0.043	-0.036		-0.085
Rsquare	0.981	0.959	0.974	0.926	0.955	0.879	0.847	0.984		0.953

In Situ Respiration Test #5 (17 - 23 Mar 1992)

Time (hrs)	A2B	A3A	A5C	A6A	Time (hrs)	P4B	P4C	P6A	P6B	P6C
0	14.9	18.6	9.0	7.8	0	20.9	20.9	20.9	20.9	20.8
3	10.4	17.6	8.8	8.6	3	20.9	20.9	20.9	20.9	20.9
19	9.2	12.2	7.8	5.6	19	20.3	20.1	20.0	19.9	20.1
49	1.4	6.1	6.5	4.2	49	18.5	19.5	19.4	18.8	19.8
137		4.8		1.9	137	16.5	18.1	17.1	16.2	18.0
Intercept	13.24	15.82	8.93	7.46	Intercept	20.79	20.74	20.80	20.76	20.77
Slope	-0.240	-0.095	-0.051	-0.044	Slope	-0.033	-0.020	-0.027	-0.034	-0.020
Rsquare	0.920	0.722	0.991	0.857	Rsquare	0.960	0.960	0.987	0.986	0.978

(hrs)	C1B	C2A	C6A	C6B	C6C
0	8.8	20.8	20.9	13.0	13.1
3	8.8	19.6	20.5	12.8	12.8
19	7.1	18.5	18.4	11.4	12.4
49	7.1	17.1	18.0	10.1	10.1
137	4.0	15.9	14.8	10.0	
Intercept	8.55	19.66	20.24	12.31	13.16
Slope	-0.034	-0.031	-0.041	-0.020	-0.060
Rsquare	0.942	0.805	0.924	0.662	0.965

APPENDIX C: Paired Oxygen Consumption Rates [%/hr] and Temperature [°C]

	ISRT 1 1-7 Oct 91		ISRT 2 10-14 Nov 91		ISRT 3 7-14 Dec 91		ISRT 4 28 Jan-2 Feb 9		ISRT 5 17-23 Mar 92		ISRT 6 18-23 Apr 92		ISRT 7 13-20 June 92		ISRT 8 9-19 Aug 92		ISRT 9 30 Oct -12 No	
	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp
A1A																		
A1B	0.697	10.100			0.150	11.650	0.128	10.200										
A1C							0.023	10.533										
A2A																		
A2B	0.176	10.892					0.239	10.095	0.240	17.160					0.331	16.714		
A2C	0.112	11.211					0.088	10.603										
A3A	0.059	10.467							0.095	14.431	0.532	17.469			0.413	15.989		
A3B							0.096	9.994										
A3C	0.024	11.833					0.114	10.658										
A4A																		
A4B							0.051	9.175										
A4C							0.016	9.200			0.215	18.375	0.037	24.173				
A5A																		
A5B	0.244	11.638																
A5C							0.039	9.550	0.051	16.271	0.122	19.113						
A6A	0.146	10.393					0.032	9.950	0.044	13.867	0.238	17.388			0.254	15.736		
A6B	0.155	11.638									0.215	18.456			0.190	16.800		
A6C	0.024	11.854			0.149	9.783					0.149	19.113					0.277	15.538
A7A																		
A7B																		
A7C																		
A8A																		
A8B																		
A8C																		
AVE	0.182	11.114			0.149	10.717	0.083	9.996	0.108	15.432	0.245	18.319	0.037	24.173	0.297	16.310	0.277	15.538

Warm Water Plot

142

	ISRT 1 1-7 Oct 91		ISRT 2 10-14 Nov 91		ISRT 3 7-14 Dec 91		ISRT 4 28 Jan-2 Feb 9		ISRT 5 17-23 Mar 92		ISRT 6 18-23 Apr 92		ISRT 7 13-20 June 92		ISRT 8 9-19 Aug 92		ISRT 9 30 Oct -12 No	
	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp
P1A	0.050	6.233					0.024	0.863							0.134	13.293	0.065	4.775
P1B	0.041	6.842					0.022	0.442							0.145	16.386	0.048	4.083
P1C	0.029	6.433					0.017	-0.575							0.114	18.143	0.020	2.238
P2A	0.027	6.233					0.027	0.863									0.050	4.775
P2B	0.038	6.842					0.021	0.442							0.166	16.386	0.052	4.083
P2C	0.030	6.433					0.017	-0.575							0.151	18.143	0.023	2.238
P3A	0.027	6.233					0.025	0.863							0.174	13.293	0.062	4.775
P3B	0.034	6.842					0.024	0.442							0.177	16.386	0.074	4.083
P3C	0.016	6.433					0.015	-0.575					0.083	17.994	0.143	18.143	0.030	2.238
P4A	0.041	6.233	0.040	3.450	0.032	2.050	0.025	0.863							0.098	13.293	0.067	4.775
P4B	0.051	6.842	0.048	2.833	0.037	1.420	0.030	0.442	0.033	-0.107	0.040	-0.220	0.119	11.550	0.196	16.386	0.074	4.083
P4C	0.040	6.433	0.036	1.100	0.022	0.093	0.020	-0.575	0.020	-0.913	0.021	-0.810	0.099	17.994			0.034	2.238
P5A	0.039	6.233					0.025	0.863			0.026	0.090			0.081	13.293	0.058	4.775
P5B	0.057	6.842					0.027	0.442					0.117	11.550	0.188	16.386	0.069	4.083
P5C	0.046	6.433					0.023	-0.575							0.164	18.143	0.034	2.238
P6A	0.033	6.233	0.049	3.450	0.032	2.050	0.023	0.863	0.027	0.240	0.025	0.090					0.048	4.775
P6B	0.073	6.842	0.066	2.833	0.033	1.420	0.076	0.442	0.034	-0.107	0.026	-0.220			0.132	16.386	0.069	4.083
P6C	0.054	6.433	0.027	1.100	0.021	0.093	0.021	-0.575	0.020	-0.913	0.015	-0.810	0.100	17.994	0.193	18.143	0.033	2.238
P7A																	0.024	5.413
P7B																	0.013	4.413
P7C																	0.005	2.238
P8A																		
P8B																		
P8C																		
AVE	0.041	6.503	0.044	2.461	0.030	1.188	0.026	0.243	0.027	-0.360	0.026	-0.313	0.104	15.416	0.150	16.147	0.045	3.745

Passive Warming Plot

143

	ISRT 1 1-7 Oct 91		ISRT 2 10-14 Nov 91		ISRT 3 7-14 Dec 91		ISRT 4 28 Jan-2 Feb 9		ISRT 5 17-23 Mar 92		ISRT 6 18-23 Apr 92		ISRT 7 13-20 June 92		ISRT 8 9-19 Aug 92		ISRT 9 30 Oct -12 No	
	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp
H1A																	0.217	7.675
H1B																	0.160	7.538
H1C																	0.093	7.638
H2A																	0.217	6.775
H2B																	0.147	9.250
H2C																		
H3A																	0.059	7.225
H3B																		
H3C																		
H4A																	0.149	6.842
H4B																	0.065	8.750
H4C																	0.063	10.499
H5A																		
H5B																		
H5C																	0.126	10.268
H6A																	0.253	6.950
H6B																		
H6C																		
AVE																	0.141	8.128

Heat Tape Plot

144

	ISRT 1 1-7 Oct 91		ISRT 2 10-14 Nov 91		ISRT 3 7-14 Dec 91		ISRT 4 28 Jan-2 Feb 9		ISRT 5 17-23 Mar 92		ISRT 6 18-23 Apr 92		ISRT 7 13-20 June 92		ISRT 8 9-19 Aug 92		ISRT 9 30 Oct -12 No	
	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp
C1A	0.097	6.950	0.086	2.525	0.045	1.180	0.038	0.250									0.068	2.483
C1B	0.072	7.000	0.065	1.325	0.040	0.210	0.040	-0.400	0.034	-0.830	0.059	-0.863			0.247	12.500	0.069	1.713
C1C			0.046	0.375									0.025	8.060	0.027	13.750	0.035	0.944
C2A	0.067	6.950					0.029	0.250	0.031	-0.240	0.044	-0.375			0.097	10.771	0.079	2.438
C2B	0.039	7.000																
C2C															0.029	13.750	0.044	0.944
C3A	0.035	6.950					0.015	0.250										
C3B							0.122	-0.400							0.325	12.500		
C3C															0.040	13.750	0.036	0.944
C4A	0.063	6.950					0.085	0.250										
C4B	0.058	7.000					0.086	-0.400							0.284	12.500		
C4C															0.049	13.750	0.046	0.944
C5A	0.101	6.950																
C5B																	0.049	1.713
C5C							0.043	-1.263							0.071	13.750	0.043	0.944
C6A	0.113	6.950	0.085	2.525	0.048	1.180	0.036	0.250	0.041	-0.240	0.064	-0.375					0.071	2.483
C6B			0.125	1.325	0.076	0.210			0.020	-0.830					0.123	12.500	0.043	1.713
C6C									0.060	-1.550					0.067	13.750	0.036	0.944
C7A																		
C7B																	0.043	2.844
C7C																		
C8A																	0.042	4.125
C8B																	0.040	2.844
C8C																		
AVE	0.072	6.967	0.082	1.615	0.052	0.695	0.055	-0.135	0.037	-0.738	0.056	-0.538	0.025	8.060	0.124	13.025	0.050	1.868

Control Plot

145

	ISRT 10 Jan 93		ISRT 11 8-15 Jan 93		ISRT 12 24 Feb-3 Mar		ISRT 13 24-31 Mar 93		ISRT 14 7-13 May 93		ISRT 15 7-11 Jul 93		ISRT 16 24-28 Jul 93		ISRT 17 20-26 Oct 93		ISRT 18 16-21 Nov 93	
	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp
A1A																		
A1B											0.356	19.433			0.113	2.280		
A1C											0.053	23.100						
A2A			0.000	15.762														
A2B	0.288	18.059			0.172	15.645	0.110	16.665	0.134	9.037	0.221	19.322	0.370	16.523	0.036	4.493		
A2C					0.085	14.752	0.090	16.418	0.125	9.197								
A3A			0.000	15.875							0.209	15.242	0.311	14.181	0.082	5.235		
A3B			0.000	17.120														
A3C			0.005	18.075					0.042	9.210	0.093	22.000	0.103	18.784	0.015	1.845		
A4A			0.000	15.520														
A4B	0.246	17.029			0.189	13.860	0.185	14.753										
A4C	0.037	15.940			0.015	12.200	0.017	13.420			0.017	20.511						
A5A			0.000	15.740														
A5B			0.000	16.770														
A5C	0.020	16.610			0.012	12.630	0.016	13.980										
A6A	0.134	16.146			0.071	13.597	0.063	13.763			0.013	15.561			0.138	4.923		
A6B	0.126	17.128			0.055	14.140	0.046	15.027	0.022	8.777	0.014	18.933						
A6C	0.098	16.620			0.024	12.630	0.019	13.980										
A7A	0.628	16.360	0.000	15.847									0.231	14.075				
A7B			0.027	17.207														
A7C			0.000	18.200														
A8A			0.000	15.733									0.074	13.650				
A8B			0.000	17.553														
A8C									0.065	9.193								
AVE	0.197	16.737	0.003	16.617	0.078	13.682	0.068	14.751	0.078	9.083	0.122	19.263	0.218	15.443	0.077	3.755		

▲ Warm Water Circulation Turned Off

Warm Water Plot

146

	ISRT 10 Jan 93		ISRT 11 8-15 Jan 93		ISRT 12 24 Feb-3 Mar		ISRT 13 24-31 Mar 93		ISRT 14 7-13 May 93		ISRT 15 7-11 Jul 93		ISRT 16 24-28 Jul 93		ISRT 17 20-26 Oct 93		ISRT 18 16-21 Nov 93	
	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp
P1A	0.047	1.610	0.076	1.660									0.159	12.850			0.102	4.788
P1B	0.031	1.144	0.048	1.173					0.048	0.967			0.139	15.475			0.060	3.100
P1C	0.023	0.000	0.011	0.027					0.048	3.700			0.095	20.200			0.010	2.500
P2A			0.000	1.660									0.071	12.850			0.048	4.788
P2B	0.037	1.144	0.043	1.173			0.038	0.180	0.057	0.967	0.146	13.878	0.155	15.475	0.066	5.580	0.054	3.100
P2C			0.014	0.027					0.047	3.700			0.111	20.200			0.013	2.500
P3A	0.053	1.610	0.057	1.660									0.149	12.850			0.066	4.788
P3B			0.053	1.173									0.182	15.475			0.063	3.100
P3C	0.025	0.000	0.020	0.027					0.044	3.700			0.105	20.200	0.027	5.167	0.019	2.500
P4A	0.051	1.610	0.050	1.660	0.037	0.820	0.049	0.480			0.095	11.283	0.105	12.850	0.080	7.190	0.062	4.788
P4B	0.041	1.144	0.000	1.173	0.032	0.427												
P4C	0.032	0.000	0.000	0.027	0.026	-0.367	0.030	-0.567	0.063	3.700	0.144	18.111						
P5A	0.046	1.610	0.047	1.660	0.028	0.820	0.036	0.480			0.059	11.283	0.085	12.850	0.057	7.190		
P5B	0.051	1.144	0.069	1.173	0.051	0.427	0.064	0.180	0.104	0.967	0.244	13.878	0.218	15.475	0.089	5.580		
P5C	0.035	0.000	0.029	0.027	0.023	-0.367	0.028	-0.567	0.068	3.700	0.166	18.111	0.177	20.200	0.026	5.167	0.023	2.500
P6A	0.043	1.610	0.043	1.660									0.091	12.850			0.039	4.788
P6B			0.055	1.173					0.078	0.967			0.167	15.475			0.064	3.100
P6C	0.034	0.000	0.022	0.027					0.089	3.700			0.167	20.200			0.024	2.500
P7A	0.018	2.344	0.000	2.530									0.104	10.200				
P7B	0.014	1.623	0.029	1.780					0.037	3.267			0.073	14.800			0.035	4.625
P7C	0.006	1.035	0.016	1.080					0.044	6.150			0.096	20.225			0.022	3.388
P8A			0.000	2.530														
P8B	0.021	1.623	0.021	1.780					0.036	3.267								
P8C	0.026	1.035	0.036	1.080														
AVE	0.033	1.068	0.031	1.164	0.033	0.293	0.041	0.031	0.059	2.981	0.142	14.424	0.129	15.826	0.057	5.979	0.044	3.553

Passive Warming Plot

147

	ISRT 10 Jan 93		ISRT 11 8-15 Jan 93		ISRT 12 24 Feb-3 Mar		ISRT 13 24-31 Mar 93		ISRT 14 7-13 May 93		ISRT 15 7-11 Jul 93		ISRT 16 24-28 Jul 93		ISRT 17 20-26 Oct 93		ISRT 18 16-21 Nov 93	
	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp
H1A	0.190	8.760	0.000	8.800	0.525	8.460			0.113	10.750			0.142	14.200			0.122	14.000
H1B	0.107	9.933	0.086	9.720	0.157	10.260			0.125	12.017			0.546	17.375	0.215	16.060	0.259	15.000
H1C	0.044	10.400			0.137	11.700							0.217	20.575				
H2A	0.221	8.440	0.000	8.360									0.189	13.600			0.139	14.000
H2B	0.033	11.700	0.000	11.540														
H2C	0.055	13.930											0.147	23.625				
H3A	0.204	8.600											0.197	13.900				
H3B							0.091	13.920										
H3C			0.064	11.720	0.099	10.470	0.189	11.540			0.372	17.930			0.032	18.050		
H4A	0.109	8.278											0.092	13.283				
H4B	0.025	10.956																
H4C			0.000	12.897														
H5A			0.000	8.042							0.116	12.677	0.066	13.029				
H5B	0.152	10.362	0.000	10.211			0.129	10.582			0.262	17.352	0.394	17.677				
H5C																		
H6A			0.000	7.900									0.188	12.775				
H6B																		
H6C	0.009	12.359	0.000	12.220														
AVE	0.104	10.338	0.015	10.141	0.230	10.223	0.136	12.014	0.119	11.384	0.250	15.986	0.218	16.004	0.124	17.055	0.174	14.333

Heat Tape Plot

	ISRT 10 Jan 93		ISRT 11 8-15 Jan 93		ISRT 12 24 Feb-3 Mar		ISRT 13 24-31 Mar 93		ISRT 14 7-13 May 93		ISRT 15 7-11 Jul 93		ISRT 16 24-28 Jul 93		ISRT 17 20-26 Oct 93		ISRT 18 16-21 Nov 93	
	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp
C1A	0.040	0.767			0.034	0.200	0.035	0.000	0.052	-0.100								
C1B	0.047	0.187	0.028	0.230	0.027	-0.340	0.040	-0.480	0.052	-0.470	0.158	12.250	0.145	13.925	0.048	4.070	0.036	1.838
C1C			0.002	-0.360					0.003	-0.570	0.025	14.633	0.017	16.575	0.016	2.920	0.021	5.250
C2A	0.087	0.767	0.034	0.800					0.075	-0.100	0.102	10.300	0.103	11.304	0.047	5.080	0.010	2.925
C2B																		
C2C	0.011	-0.520	0.000	-0.360					0.003	-0.570			0.014	16.575			0.020	5.250
C3A																		
C3B			0.025	0.230					0.072	-0.470			0.121	13.925			0.027	1.838
C3C			0.014	-0.360									0.026	16.575			0.014	5.250
C4A																		
C4B			0.000	0.230					0.075	-0.470			0.138	13.925			0.015	5.250
C4C			0.052	-0.360									0.028	16.575				
C5A			0.013	0.800									0.092	11.304				
C5B	0.032	0.187	0.010	0.230	0.028	-0.340	0.023	-0.480			0.112	12.250	0.081	13.925	0.030	5.080		
C5C			0.002	-0.360									0.038	16.575	0.031	4.070		
C6A	0.042	0.767	0.000	0.800	0.034	0.200	0.032	0.000			0.100	10.300	0.078	11.304			0.021	5.250
C6B	0.025	0.187	0.017	0.230	0.027	-0.340	0.026	-0.480	0.046	-0.470	0.094	12.250	0.049	13.925			0.023	1.838
C6C	0.067	-0.520	0.012	-0.360					0.024	-0.570			0.033	16.575	0.025	2.920	0.023	5.250
C7A																		
C7B	0.015	1.067	0.023	1.250					0.051	0.988			0.076	12.267			0.025	2.538
C7C	0.018	-0.413	0.001	-0.310									0.060	16.133			0.009	1.625
C8A	0.030	1.067																
C8B	0.025	1.067	0.000	1.250					0.054	0.675			0.088	12.267			0.033	2.538
C8C	0.012	-0.513	0.001	-0.310														
AVE	0.035	0.315	0.013	0.182	0.030	-0.124	0.031	-0.288	0.046	-0.193	0.098	11.997	0.070	14.333	0.033	4.023	0.021	3.588

Control Plot

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Warm Water Plot

	ISRT 19 21-28 Dec 93		ISRT 20 8-15 Jan 94		ISRT 21 19-24 Feb 94		ISRT 22 24-30 Mar 94		ISRT 23 16-24 Apr 94		ISRT 24 8-12 May 94		ISRT 25 6-11 Jun 94		ISRT 26 2-9 Jul 94		Averaged Over Period 2 Rate
	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	
A1A																	
A1B															0.026	6.710	0.245
A1C			0.002	0.580	0.000	-0.175	0.002	-0.600	0.005	-0.750	0.002	-0.650			0.000	5.380	0.011
A2A			0.000	0.242													0.000
A2B															0.064	7.773	0.198
A2C																	0.100
A3A			0.000	0.435	0.000	-0.131	0.000	-0.450			0.039	0.056			0.006	7.560	0.155
A3B			0.000	0.395			0.000	-2.038									0.020
A3C							0.001	-3.094									0.049
A4A			0.000	0.660			0.000	-0.533									0.000
A4B					0.003	-0.667	0.001	-1.158									0.112
A4C									0.015	-1.733			0.001	6.640			0.041
A5A			0.000	0.620													0.000
A5B			0.000	-0.103													0.062
A5C													0.001	6.430	0.004	7.673	0.033
A6A					0.027	-0.138	0.000	-0.567	0.031	-0.731	0.044	-0.683			0.000	11.012	0.079
A6B					0.011	-0.758	0.018	-1.292	0.024	-0.842			0.020	0.320	0.012	5.533	0.069
A6C					0.004	-0.467	0.010	-3.133	0.022	-1.783	0.014	0.113	0.013	0.400	0.000	7.673	0.044
A7A			0.000	0.387									0.009	6.430	0.001	11.012	0.227
A7B									0.019	-1.394	0.002	-0.158					0.016
A7C			0.000	-4.880					0.020	-1.678	0.002	0.050					0.005
A8A			0.000	0.193			0.000	-0.200							0.000	8.400	0.019
A8B			0.000	1.120													0.000
A8C													0.038	6.440	0.125	6.050	0.076
AVE			0.000	-0.032	0.008	-0.389	0.003	-1.307	0.019	-1.273	0.017	-0.212	0.014	4.443	0.022	7.707	0.068

	ISRT 19 21-28 Dec 93		ISRT 20 8-15 Jan 94		ISRT 21 19-24 Feb 94		ISRT 22 24-30 Mar 94		ISRT 23 16-24 Apr 94		ISRT 24 8-12 May 94		ISRT 25 6-11 Jun 94		ISRT 26 2-9 Jul 94		Averaged Over Period 2
	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate
P1A			0.063	2.100					0.070	0.142					0.137	10.870	0.084
P1B			0.040	1.040					0.039	-1.017					0.118	12.970	0.065
P1C			0.010	-0.007					0.024	-0.894					0.045	17.387	0.037
P2A			0.000	2.100											0.066	10.870	0.036
P2B	0.044	1.460	0.036	1.040	0.029	0.188	0.047	-0.625	0.042	-1.017	0.051	-0.588	0.101	9.763	0.110	12.970	0.067
P2C			0.012	-0.007					0.033	-0.894					0.059	17.387	0.046
P3A			0.048	2.100					0.048	0.142	0.053	0.825	0.087	7.713	0.120	10.870	0.074
P3B			0.045	1.040					0.045	-1.017	0.049	-0.588	0.096	9.763	0.121	12.970	0.080
P3C	0.018	0.600	0.017	-0.007	0.016	-0.925	0.029	-0.933	0.030	-0.894	0.040	2.850	0.068	15.067	0.064	17.387	0.043
P4A	0.050	2.710	0.042	2.100	0.033	1.125									0.125	10.870	0.060
P4B			0.000	1.040											0.134	12.970	0.060
P4C			0.000	-0.007													0.039
P5A			0.040	2.100	0.025	1.125					0.099	0.825	0.063	7.713	0.094	10.870	0.053
P5B	0.065	1.460	0.060	1.040	0.047	0.188	0.072	-0.325	0.054	-1.017	0.088	-0.588	0.146	9.763	0.126	12.970	0.095
P5C	0.022	0.600	0.025	-0.007	0.020	-0.925	0.042	-0.933	0.031	-0.894	0.056	2.850	0.114	15.067	0.082	17.387	0.059
P6A			0.035	2.100													0.041
P6B			0.046	1.040											0.090	12.970	0.072
P6C			0.018	-0.007			0.026	-0.933							0.088	17.387	0.056
P7A			0.000	3.060													0.029
P7B			0.025	2.110											0.098	14.300	0.040
P7C			0.013	1.170					0.016	0.133					0.093	19.520	0.035
P8A			0.000	3.060													0.000
P8B			0.018	2.110			0.055	0.975	0.036	1.342	0.054	3.763					0.034
P8C			0.031	1.170			0.062	0.350									0.039
AVE	0.040	1.366	0.026	1.312	0.028	0.129	0.048	-0.346	0.039	-0.490	0.061	1.169	0.097	10.693	0.098	14.051	0.052

Passive Warming Plot

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	ISRT 19 21-28 Dec 93		ISRT 20 8-15 Jan 94		ISRT 21 19-24 Feb 94		ISRT 22 24-30 Mar 94		ISRT 23 16-24 Apr 94		ISRT 24 8-12 May 94		ISRT 25 6-11 Jun 94		ISRT 26 2-9 Jul 94		Averaged Over Period 2 Rate
	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	
H1A																	0.187
H1B	0.048	13.820	0.071	13.000	0.083	11.800											0.169
H1C					0.005	10.975											0.099
H2A			0.000	12.420													0.128
H2B			0.000	12.980													0.045
H2C					0.001	12.550					0.001	16.725			0.016	21.500	0.052
H3A																	0.154
H3B															0.089	16.440	0.187
H3C			0.021	12.100	0.001	10.275					0.011	15.513			0.020	20.410	0.030
H4A																	0.088
H4B															0.076	16.103	0.055
H4C			0.000	12.197	0.001	12.204					0.001	16.090			0.007	21.208	0.012
H5A	0.000	11.365	0.000	10.828													0.037
H5B	0.000	12.989	0.000	11.858	0.072	10.979					0.048	11.575	0.059	14.115	0.046	15.722	0.106
H5C																	0.126
H6A			0.000	10.120													0.110
H6B											0.004	10.875	0.089	13.500			0.047
H6C			0.000	11.840											0.048	20.740	0.014
AVE	0.016	12.725	0.010	11.927	0.027	11.464					0.013	14.156	0.074	13.808	0.043	18.875	0.091

Heat Tape Plot

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	ISRT 19 21-28 Dec 93		ISRT 20 8-15 Jan 94		ISRT 21 19-24 Feb 94		ISRT 22 24-30 Mar 94		ISRT 23 16-24 Apr 94		ISRT 24 8-12 May 94		ISRT 25 6-11 Jun 94		ISRT 26 2-9 Jul 94		Averaged Over Period 2
	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate	Temp	Rate
C1A											0.035	-0.175					0.053
C1B	0.039	0.460	0.023	-0.670	0.029	-2.638			0.012	-1.060	0.002	-0.450					0.062
C1C	0.006	4.053	0.001	0.680	0.002	-0.788			0.016	-1.520			0.008	6.325			0.016
C2A	0.041	1.430	0.028	0.600	0.027	-0.288			0.039	-0.510					0.084	7.360	0.057
C2B																	0.039
C2C			0.000	0.680					0.018	-1.520							0.015
C3A													0.049	0.400	0.105	7.360	0.051
C3B			0.021	-0.670											0.001	9.560	0.089
C3C			0.011	0.680					0.021	-1.520	0.001	-0.450	0.016	6.325	0.001	11.940	0.018
C4A																	0.074
C4B			0.000	-0.670													0.092
C4C			0.043	0.680													0.039
C5A			0.011	0.600	0.027	-0.288									0.027	7.360	0.043
C5B			0.008	-0.670	0.002	-2.638							0.013	2.600			0.035
C5C			0.002	0.680									0.012	6.325			0.028
C6A			0.000	0.600													0.053
C6B	0.014	0.460	0.014	-0.670					0.045	-1.060	0.012	-0.438	0.010	2.600			0.044
C6C			0.010	0.680	0.008	-0.788			0.044	-1.520	0.001	-0.450	0.012	6.325			0.030
C7A																	
C7B			0.020	0.660													0.036
C7C			0.001	-1.580					0.016	-1.000			0.006	3.925			0.016
C8A																	0.048
C8B			0.000	0.660													0.016
C8C			0.001	-1.580					0.011	-1.000							0.016
AVE	0.025	1.601	0.011	0.038	0.016	-1.238			0.024	-1.223	0.010	-0.393	0.016	4.353	0.044	8.716	0.042

Control Plot

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APPENDIX D: Plot Average Respiration Rates by Depth

Warm Water Plot

	5.25 - 7.5 ft		4.25 - 4.5 ft		2 - 2.5 ft	
	O2 Rat [%/hr]	Temp [deg C]	O2 Rat [%/hr]	Temp [deg C]	O2 Rat [%/hr]	Temp [deg C]
ISRT # 1	0.102	10.430	0.318	11.067	0.053	11.633
ISRT # 2						
ISRT # 3			0.150	11.650	0.149	9.783
ISRT # 4	0.032	9.950	0.129	9.866	0.056	10.109
ISRT # 5	0.070	14.149	0.240	17.160	0.051	16.271
ISRT # 6	0.385	17.429	0.215	18.456	0.162	18.867
ISRT # 7					0.037	24.173
ISRT # 8	0.334	15.863	0.261	16.757		
ISRT # 9	0.277	15.538				
ISRT # 10	0.381	16.253	0.220	17.405	0.052	16.390
ISRT # 11	0.000	15.746	0.007	17.163	0.002	18.138
ISRT # 12	0.071	13.597	0.138	14.548	0.034	13.053
ISRT # 13	0.063	13.763	0.114	15.482	0.035	14.450
ISRT # 14			0.078	8.907	0.077	9.200
ISRT # 15	0.111	15.402	0.197	19.229	0.054	21.870
ISRT # 16	0.205	13.969	0.370	16.523	0.103	18.784
ISRT # 17	0.110	5.079	0.074	3.387	0.015	1.845
ISRT # 18						
ISRT # 19						
ISRT # 20	0.000	0.423	0.000	0.471	0.001	-2.150
ISRT # 21	0.014	-0.135	0.007	-0.713	0.002	-0.321
ISRT # 22	0.000	-0.438	0.006	-1.496	0.004	-2.276
ISRT # 23	0.031	-0.731	0.021	-1.118	0.015	-1.486
ISRT # 24	0.044	-0.683	0.002	-0.158	0.014	-0.108
ISRT # 25	0.020	0.320	0.013	0.400	0.012	6.485
ISRT # 26	0.012	5.533	0.020	7.478	0.025	8.371

Passive Warming Plot

	5.25 - 7.5 ft		4.25 - 4.5 ft		2 - 2.5 ft	
	O2 Rat [%/hr]	Temp [deg C]	O2 Rat [%/hr]	Temp [deg C]	O2 Rat [%/hr]	Temp [deg C]
ISRT # 1	0.036	6.233	0.049	6.842	0.036	6.433
ISRT # 2	0.045	3.450	0.057	2.833	0.031	1.100
ISRT # 3	0.032	2.050	0.035	1.420	0.021	0.093
ISRT # 4	0.025	0.863	0.033	0.442	0.019	-0.575
ISRT # 5	0.027	0.240	0.034	-0.107	0.020	-0.913
ISRT # 6	0.025	0.090	0.033	-0.220	0.018	-0.810
ISRT # 7			0.118	11.550	0.094	17.994
ISRT # 8	0.122	13.293	0.167	16.386	0.153	18.143
ISRT # 9	0.053	4.866	0.057	4.130	0.026	2.238
ISRT # 10	0.043	1.732	0.032	1.304	0.026	0.296
ISRT # 11	0.034	1.878	0.040	1.325	0.019	0.290
ISRT # 12	0.032	0.820	0.041	0.427	0.024	-0.367
ISRT # 13	0.042	0.480	0.051	0.180	0.029	-0.567
ISRT # 14			0.060	1.734	0.058	4.050
ISRT # 15	0.077	11.283	0.195	13.878	0.155	18.111
ISRT # 16	0.109	12.471	0.156	15.363	0.125	20.204
ISRT # 17	0.069	7.190	0.077	5.580	0.026	5.167
ISRT # 18	0.064	4.788	0.055	3.405	0.019	2.648
ISRT # 19	0.050	2.710	0.055	1.460	0.020	0.600
ISRT # 20	0.029	2.340	0.034	1.308	0.016	0.287
ISRT # 21	0.029	1.125	0.038	0.188	0.018	-0.925
ISRT # 22			0.058	0.008	0.040	-0.612
ISRT # 23	0.059	0.142	0.043	-0.545	0.027	-0.689
ISRT # 24	0.076	0.825	0.061	0.500	0.048	2.850
ISRT # 25	0.075	7.713	0.115	9.763	0.091	15.067
ISRT # 26	0.108	10.870	0.114	13.160	0.072	17.743

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Control Plot

ISRT #	5.25 - 7.5 ft O2 Rat [%/hr]	5.25 - 7.5 ft Temp [deg C]	4.25 - 4.5 ft O2 Rat [%/hr]	4.25 - 4.5 ft Temp [deg C]	2 - 2.5 ft O2 Rat [%/hr]	2 - 2.5 ft Temp [deg C]
ISRT # 1	0.079	6.950	0.057	7.000		
ISRT # 2	0.085	2.525	0.095	1.325	0.046	0.375
ISRT # 3	0.046	1.180	0.058	0.210		
ISRT # 4	0.041	0.250	0.083	-0.400	0.043	-1.263
ISRT # 5	0.036	-0.240	0.027	-0.830	0.060	-1.550
ISRT # 6	0.054	-0.375	0.059	-0.863		
ISRT # 7					0.025	8.060
ISRT # 8	0.097	10.771	0.245	12.500	0.047	13.750
ISRT # 9	0.065	2.882	0.049	2.165	0.040	0.944
ISRT # 10	0.049	0.842	0.029	0.539	0.027	-0.492
ISRT # 11	0.016	0.800	0.015	0.521	0.010	-0.348
ISRT # 12	0.034	0.200	0.027	-0.340		
ISRT # 13	0.034	0.000	0.030	-0.480		
ISRT # 14			0.059	-0.178	0.021	-0.259
ISRT # 15	0.101	10.300	0.121	12.250	0.025	14.633
ISRT # 16	0.090	11.545	0.102	13.649	0.031	16.512
ISRT # 17	0.039	5.080	0.040	4.070	0.021	2.920
ISRT # 18	0.022	2.732	0.028	2.013	0.017	4.732
ISRT # 19	0.041	1.430	0.027	0.460	0.006	4.053
ISRT # 20	0.013	0.600	0.012	-0.290	0.009	0.115
ISRT # 21	0.027	-0.288	0.015	-2.638	0.005	-0.788
ISRT # 22						
ISRT # 23	0.039	-0.510	0.029	-1.060	0.021	-1.371
ISRT # 24	0.035	-0.175	0.012	-0.438	0.002	-0.450
ISRT # 25	0.049	0.400	0.012	2.600	0.011	5.845
ISRT # 26	0.072	7.360	0.001	9.560	0.001	11.940

Heat Tape Plot

ISRT #	7 - 7.5 ft O2 Rat [%/hr]	7 - 7.5 ft Temp [deg C]	4 - 4.5 ft O2 Rat [%/hr]	4 - 4.5 ft Temp [deg C]	2 - 2.5 ft O2 Rat [%/hr]	2 - 2.5 ft Temp [deg C]
ISRT # 9	0.179	7.093	0.124	8.513	0.094	9.468
ISRT # 10	0.181	8.520	0.079	10.738	0.036	12.230
ISRT # 11	0.000	8.276	0.029	10.490	0.021	12.279
ISRT # 12	0.525	8.460	0.128	10.365	0.137	11.700
ISRT # 13			0.159	11.061	0.091	13.920
ISRT # 14	0.113	10.750	0.125	12.017		
ISRT # 15	0.116	12.677	0.317	17.641		
ISRT # 16	0.146	13.465	0.470	17.526	0.182	22.100
ISRT # 17			0.215	16.060	0.032	18.050
ISRT # 18	0.131	14.000	0.259	15.000		
ISRT # 19	0.000	11.365	0.024	13.405		
ISRT # 20	0.000	11.123	0.024	12.613	0.007	12.046
ISRT # 21	0.001	10.275	0.077	11.390	0.002	11.910
ISRT # 24			0.026	11.225	0.005	16.109
ISRT # 25			0.074	13.808		
ISRT # 26			0.070	16.088	0.023	20.965

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APPENDIX E: Comparison of Calculated Biodegradation Rates by Depth

Warm Water Plot

Units = [mg-hexane/kg-soil/day]

	5.25 - 7.5 ft		4.25 - 4.5 ft		2 - 2.5 ft	
	Simple	Hinchee	Simple	Hinchee	Simple	Hinchee
ISRT # 1	1.958	1.984	6.106	6.171	1.018	1.027
ISRT # 2						
ISRT # 3			2.880	2.905	2.861	2.905
ISRT # 4	0.614	0.623	2.477	2.514	1.075	1.090
ISRT # 5	1.344	1.344	4.608	4.560	0.979	0.972
ISRT # 6	7.392	7.308	4.128	4.067	3.110	3.060
ISRT # 7					0.710	0.686
ISRT # 8	6.413	6.374	5.011	4.966		
ISRT # 9	5.318	5.292				
ISRT # 10	7.315	7.262	4.224	4.176	0.998	0.991
ISRT # 11	0.000	0.000	0.134	0.133	0.038	0.038
ISRT # 12	1.363	1.366	2.650	2.646	0.653	0.655
ISRT # 13	1.210	1.211	2.189	2.179	0.672	0.671
ISRT # 14	0.000	0.000	1.498	1.525	1.478	1.504
ISRT # 15	2.131	2.122	3.782	3.716	1.037	1.010
ISRT # 16	3.936	3.938	7.104	7.045	1.978	1.946
ISRT # 17	2.112	2.181	1.421	1.476	0.288	0.301
ISRT # 18						
ISRT # 19						
ISRT # 20	0.000	0.000	0.000	0.000	0.019	0.020
ISRT # 21	0.269	0.283	0.134	0.142	0.038	0.040
ISRT # 22	0.000	0.000	0.115	0.122	0.077	0.081
ISRT # 23	0.595	0.628	0.403	0.426	0.288	0.305
ISRT # 24	0.845	0.891	0.038	0.040	0.269	0.283
ISRT # 25	0.384	0.403	0.250	0.262	0.230	0.237
ISRT # 26	0.230	0.238	0.384	0.393	0.480	0.490

Passive Warming Plot

	5.25 - 7.5 ft		4.25 - 4.5 ft		2 - 2.5 ft	
	Simple	Hinchee	Simple	Hinchee	Simple	Hinchee
ISRT # 1	0.691	0.711	0.941	0.965	0.691	0.710
ISRT # 2	0.864	0.897	1.094	1.139	0.595	0.623
ISRT # 3	0.614	0.641	0.672	0.703	0.403	0.424
ISRT # 4	0.480	0.503	0.634	0.665	0.365	0.384
ISRT # 5	0.518	0.545	0.653	0.687	0.384	0.405
ISRT # 6	0.480	0.505	0.634	0.667	0.346	0.365
ISRT # 7			2.266	2.286	1.805	1.781
ISRT # 8	2.342	2.349	3.206	3.181	2.938	2.897
ISRT # 9	1.018	1.052	1.094	1.134	0.499	0.521
ISRT # 10	0.826	0.863	0.614	0.643	0.499	0.524
ISRT # 11	0.653	0.682	0.768	0.804	0.365	0.383
ISRT # 12	0.614	0.644	0.787	0.827	0.461	0.485
ISRT # 13	0.806	0.847	0.979	1.029	0.557	0.587
ISRT # 14			1.152	1.204	1.114	1.154
ISRT # 15	1.478	1.493	3.744	3.747	2.976	2.935
ISRT # 16	2.093	2.105	2.995	2.982	2.400	2.350
ISRT # 17	1.325	1.358	1.478	1.524	0.499	0.515
ISRT # 18	1.229	1.270	1.056	1.097	0.365	0.380
ISRT # 19	0.960	1.000	1.056	1.105	0.384	0.403
ISRT # 20	0.557	0.581	0.653	0.683	0.307	0.323
ISRT # 21	0.557	0.583	0.730	0.767	0.346	0.365
ISRT # 22			1.114	1.171	0.768	0.810
ISRT # 23	1.133	1.191	0.826	0.870	0.518	0.547
ISRT # 24	1.459	1.530	1.171	1.230	0.922	0.959
ISRT # 25	1.440	1.473	2.208	2.242	1.747	1.742
ISRT # 26	2.074	2.097	2.189	2.196	1.382	1.365

Control Plot

Heat Tape Plot

Units = [mg-hexane/kg-soil/day]

	Control 5.25 - 7.5 ft		Control 4.25 - 4.5 ft		Control 2 - 2.5 ft		Heat Tape 7 - 7.5 ft		Heat Tape 4 - 4.5 ft		Heat Tape 2 - 2.5 ft	
	Simple	Hinchee	Simple	Hinchee	Simple	Hinchee	Simple	Hinchee	Simple	Hinchee	Simple	Hinchee
ISRT # 1	1.517	1.556	1.094	1.122								
ISRT # 2	1.632	1.701	1.824	1.909	0.883	0.928						
ISRT # 3	0.883	0.925	1.114	1.170								
ISRT # 4	0.787	0.827	1.594	1.679	0.826	0.872						
ISRT # 5	0.691	0.728	0.518	0.547	1.152	1.219						
ISRT # 6	1.037	1.092	1.133	1.195	0.000	0.000						
ISRT # 7					0.480	0.490						
ISRT # 8	1.862	1.884	4.704	4.731	0.902	0.904	3.437	3.523	2.381	2.428	1.805	1.835
ISRT # 9	1.248	1.299	0.941	0.982	0.768	0.805	3.475	3.544	1.517	1.535	0.691	0.696
ISRT # 10	0.941	0.986	0.557	0.584	0.518	0.546	0.000	0.000	0.557	0.564	0.403	0.406
ISRT # 11	0.307	0.322	0.288	0.302	0.192	0.202	10.080	10.283	2.458	2.490	2.630	2.653
ISRT # 12	0.653	0.686	0.518	0.546					3.053	3.086	1.747	1.748
ISRT # 13	0.653	0.687	0.576	0.607					2.400	2.418		
ISRT # 14			1.133	1.192	0.403	0.424	2.170	2.195	6.086	6.013		
ISRT # 15	1.939	1.965	2.323	2.339	0.480	0.479	2.227	2.239	9.024	8.919	3.494	3.400
ISRT # 16	1.728	1.744	1.958	1.962	0.595	0.590	2.803	2.810	4.128	4.100	0.614	0.606
ISRT # 17	0.749	0.773	0.768	0.796	0.403	0.420			4.973	4.958		
ISRT # 18	0.422	0.440	0.538	0.561	0.326	0.337	2.515	2.516	0.461	0.462		
ISRT # 19	0.787	0.824	0.518	0.544	0.115	0.119	0.000	0.000	0.461	0.463	0.134	0.135
ISRT # 20	0.250	0.262	0.230	0.243	0.173	0.182	0.000	0.000	1.478	1.493	0.038	0.039
ISRT # 21	0.518	0.546	0.288	0.306	0.096	0.101	0.019	0.019				
ISRT # 22												
ISRT # 23	0.749	0.789	0.557	0.588	0.403	0.426						
ISRT # 24	0.672	0.707	0.230	0.243	0.038	0.040			0.499	0.504	0.096	0.095
ISRT # 25	0.941	0.988	0.230	0.240	0.211	0.217			1.421	1.422	0.000	0.000
ISRT # 26	1.382	1.416	0.019	0.020	0.019	0.019			1.344	1.335	0.442	0.431

APPENDIX F: In Situ Respiration Test Dates

ISRT	Type	Start Date	End Date	Comments
1	Full	1-Oct-91	7-Oct-91	10 Oct Soil heating starts
2	Abbrev.	10-Nov-91	14-Nov-91	
3	Abbrev.	7-Dec-91	14-Dec-91	
4	Full	28-Jan-92	2-Feb-92	
5	Abbrev.	17-Mar-92	23-Mar-92	
6	Abbrev.	18-Apr-92	23-Apr-92	21 Apr Insulation off Passive, plastic mulch added
7	Abbrev.	13-Jun-92	20-Jun-92	
8	Abbrev.	9-Aug-92	19-Aug-92	
9	Full	30-Oct-92	9-Nov-92	Sept Heat Tape plot installed
10	Full	8-Jan-93	13-Jan-93	
11	Abbrev.	Jan 93	Jan 93	
12	Abbrev.	24-Feb-93	3-Mar-93	
13	Abbrev.	24-Mar-93	31-Mar-93	27 Apr Insulation taken off Passive
14	Abbrev.	7-May-93	13-May-93	
15	Abbrev.	7-Jul-93	11-Jul-93	3 Jul Warm Water plot heating turned off
16	Full	24-Jul-93	28-Jul-93	22 Jul insulation taken off Warm Water plot
17	Abbrev.	24-Oct-93	26-Oct-93	26 Jul Insulation put on Passive
18	Full	16-Nov-93	21-Nov-93	
19	Abbrev.	21-Dec-93	28-Dec-93	
20	Full	8-Jan-94	15-Jan-94	
21	Abbrev.	19-Feb-94	24-Feb-94	
22	Abbrev.	19-Mar-94	24-Mar-94	
23	Full	16-Apr-94	24-Apr-94	6 Apr Insulation taken off Passive
24	Abbrev.	8-May-94	12-May-94	
25	Abbrev.	6-Jun-94	11-Jun-94	
26	Full	2-Jul-94	9-Jul-94	

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13. ABSTRACT (Maximum 200 words)

Numerous bioremediation projects have proven effective in accelerating contaminant biodegradation by injecting oxygen into the vadose zone with a technique called bioventing. In cold climates, bioremediation is limited to the summer when soil temperatures are sufficient to support microbial growth. Laboratory studies directly correlate increased biodegradation rates with temperature. By raising soil temperatures, in situ jet fuel remediation can be accelerated which was shown by a bioventing project conducted in 1991 at Eielson AFB, Alaska, where three soil warming techniques were used. Two methods actively warmed the soil -- warm water circulation and heat tape; the other passively warmed the plot with insulatory covers. All plots were compared to an uncontaminated area and an unheated contaminated control plot. This study critically analyzes the project data to determine its effectiveness in enhancing biodegradation. This study also models the temperature-biodegradation relationship at the test plots using the van't Hoff-Arrhenius equation. Using paired oxygen consumption rates and temperatures, application of the equation was valid only for the warm water and passive warming plots. This study demonstrates that bioremediation is feasible in cold climates and can be enhanced by soil warming. Soil warming can significantly decrease remediation time with acceptable cost increases.

14. SUBJECT TERMS

Bioremediation, Jet Engine Fuels, Decontamination, Soils, Microorganisms, Soil Warming, Oxygen, Bioremediation--Cold Regions, Bioventing, van't Hoff-Arrhenius Equation

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